FINAL REPORT

SFI **METAL** PRODUCTION

2015-2023

Norwegian Centre for Research-based Innovation

metal production

NTNU
Norwegian University of Science and Technology

Information about the Centre
SFI Metal Production is a Centre for research-based innovation (SFI) appointed by The Research Council of Norway from 2015-2023. A Centre for research-based innovation is a dedicated, long-term initiative designed to strengthen and further develop elite, creative research and innovation groups or to build research groups in strategically important areas.

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NTNU, Faculty of Natural Sciences, Department of Materials Science and Engineering

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Front page photo: Metal tapping from the pilot furnace in the smelting hall at SINTEF/ NTNU in Trondheim. Photo: Casper Van der Eijk

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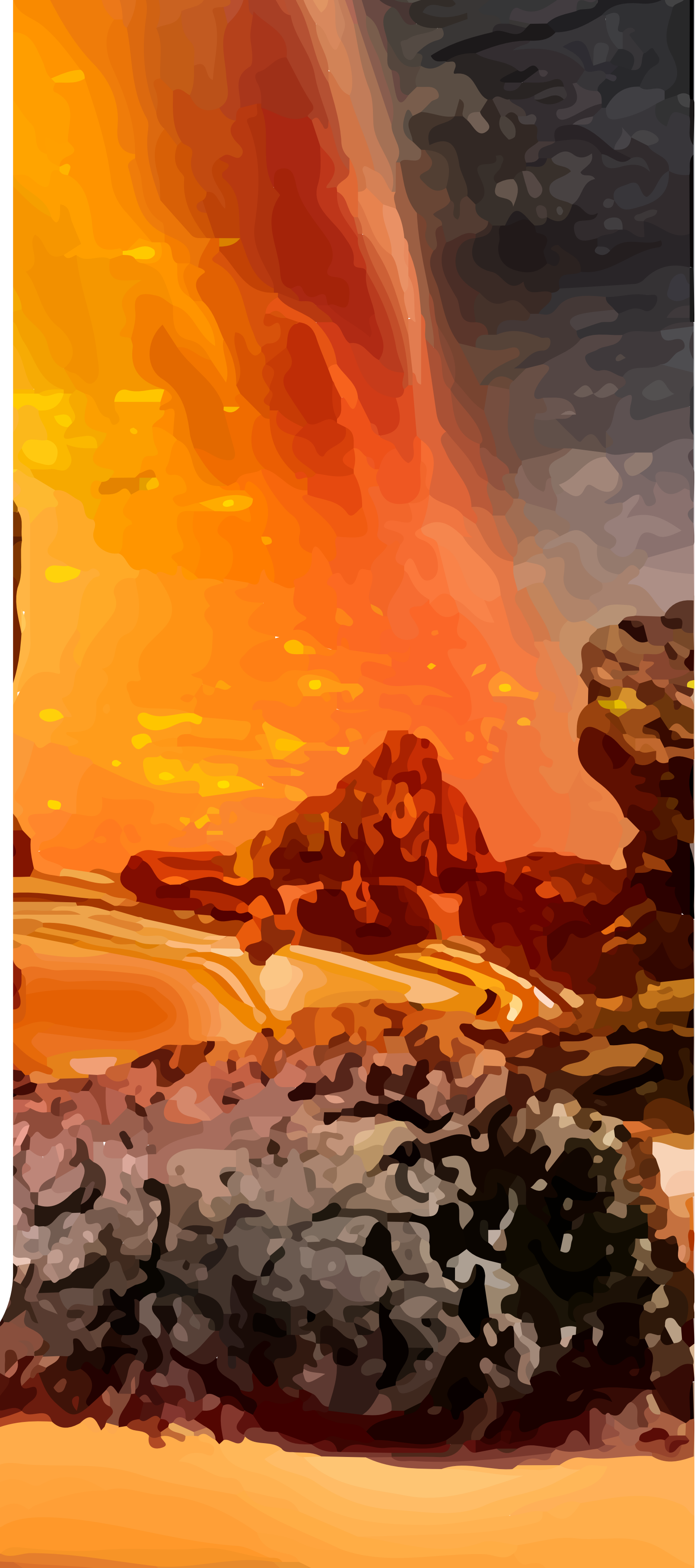

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OF THE FINAL REPORT FOR SFI METAL PRODUCTION

FOREWORD

by Centre Manager Aud Wærnes

SFI Metal Production is a Centre for Research Based Innovation that started in 2015 with a Centre period of eight years. The Centre research and education activities have covered the value chain from raw materials, through production of metals to refining and recycling of metals and metal production waste and side streams. Process modelling and Environmental challenges of metal production have also been targeted in the research activities of the Centre.

In this final report, highlights and results/outcomes from the Centre are described. Basic facts about the Centre including the organisation and financing through the lifetime of the
Centre, are all documented.

The scientific work in the Centre is reported under the 5 Research Domains into which the Centre was organised, For more detailed descriptions of individual activities, we refer to the Annual Reports in the period 2015 – 2021.

This final report is aimed at giving an overview of our common achievements during eight years of cooperation.

We are very grateful for the support during this Centre period and would like to thank all industry partners, the Norwegian research council, students, researchers and members of the Scientific Committee for their engagement and enthusiasm!

by Ida Westermann, head of department of Materials Science and Engineering (host institution)

Metal production is a core industrial sector in Norway and an important research and education area at NTNU. Primary metal production, with focus on aluminium, silicon and ferroalloys, is one of the main research topics at the Department of Materials Science and Engineering.

The SFI scheme seeks to promote innovation by providing funding for long-term research conducted in close cooperation between research-performing companies and prominent research groups. Another important long-term outcome is the education of competent post doctors, PhDs and master candidates. Through the close collaboration between the university, the research institutes and the industry partners, the candidates have learned the interplay between solving industrial questions and applied research, as well as formulating basic scientific questions based on industrial needs.

We are pleased to see that many of the young talents trained in the Centre pursue a career at our industry partners or as researchers, contributing to continue the long history of the strong collaboration triangle between academia, research institutes and industry.

We believe that the research outcome and candidates educated under the umbrella of the Centre strongly contribute to solving the challenges in the metallurgical industry; to reduce emission, reduce the energy consumption and improve the quality of the products in analogy with the Centre's vision.

I would like to acknowledge the efforts spent by all personnel and partners in the Centre. The most important resource for SFI Metal production are the scientists, students and personnel from the industrial partners.

SUMMARY ACHIEVED RESULTS 2015 - 2023

Metals are, and will continue to be, a prerequisite for modern life. Cars, aeroplanes, trains, windmills, solar panels, computers, and mobile phones - all a necessity for modern society - rely on metals. However, to achieve sustainability, metals need to be produced with an energy- and natural resources strategy of "doing more with less" with lowest possible or zero greenhouse gas emissions. Today, the Norwegian metallurgical industry has some of the lowest CO_2 footprint in the world due to a production based on renewable hydropower, and very efficient processes. However, carbon is still a necessity in the processes and CO_2 emissions are today inevitable.

The vision of the SFI Metal Production has been "Resource efficient metal production from a clean industry" reflecting the focus of the industry in 2013 – a vision that is still valid with reduction in CO_2 emissions and a more efficient use of materials and energy resources as priorities.

In order to solve the future challenges for the industry, more competence is needed on the core processes. As a result, the primary objectives of the Centre are to supply the industry with world leading fundamental competence and candidates, and to strengthen the innovation potential for the industry, and set up a collaboration platform for the Metal Producing industry in Norway.

NTNU has hosted the SFI Metal Production with a Centre Manager Aud N. Wærnes from SINTEF. The Centre has had three research partners: NTNU, SINTEF and NORCE, and eight industry partners: Hydro and Alcoa from the aluminium industry, REEL (former Alstom, GE) as an equipment vendor mainly for the Aluminium industry, Elkem, Finnfjord, Wacker from the Silicon and Ferrosilicon industry, Eramet a producer of manganese alloys, and Eramet Titanium & Iron that is producing raw material for TiO_2 pigment and pig iron. The staff at the SFI Metal Production has produced a large number of scientific publications. The Centre has more than doubled the number of journal papers (150), and conference proceedings/ presentations (180) compared to the goal for the Centre. Three books have been written during the Centre period, and the Centre staff has in addition contributed to chapters in 2 books. Furthermore, there are a large number of technical reports.

The Centre's staff have received several awards for the Scientific work, including rewards for presentations at conferences. Several researchers have also been appointed session chair at international conferences.

The impact for the industry of the Centre activities has been significant. Three license Agreements on pragmatic modelling have been finalised between R&D partners and the industry – two on aluminium and one on ferromanganese. In addition, a Spin-Off company based on a PhD -work on the development of affordable sensors for dust detection was established in 2021.

Contributions from members of the SFI staff have been very appreciated in public committees like the "Prosess21" that provides advice and recommendations on how Norway can best reduce emissions from the process industry by 2050 and at the same time facilitate sustainable growth for companies in the process industry. The Strategy work was initiated by the Ministry of Trade and Industry in 2018.

The Centre has established relevant research training for the students and researchers. PhD and Master students have worked in close collaboration with the industry. In addition to the regular courses, additional training has been arranged through meetings with general presentations related to the individual projects, general technical topics and non-technological issues like e.g. ethics in research. The Centre has succeeded in organising groups of students and researchers that work on the same subjects but with a different approach in Mn-, Si- and Al- production. Relevant research training provides interesting and high-quality candidates to recruit for the industry.

SFI Metal Production has an excellent Scientific Committee with highly acknowledge members from academia and industry. They have contributed to the scientific development of the Centre.

The SFI Metal Production constitutes a cornerstone for providing a strong research alignment and a visible European node. Four applications for the international partnerships for excellent education, research and innovation (INTPART), were approved during the Centre period. The overall goal has been to establish and develop a long-term cooperation between the institutions of NTNU, SINTEF, NORCE, and Universities in South Africa, Japan, South Korea, Canada regarding research and higher education.

Visiting senior researchers from other countries is very important for exchange of ideas and for input on the international state of the art in science. Researchers from the Centre that visited MINTEK in SA, have brought forward ideas for an EU funded projects PreMa - Energy efficient, primary production of manganese ferroalloys through the application of novel energy systems in the drying and pre-heating of furnace feed materials. Researchers in the Centre from SINTEF and NORCE have been supervisors for many of the PhD and MSc students. The Centre encourages students and researcher to make scientific publications in addition to more popular science publications.

A long Centre lifetime like an SFI, gives more in-depth research and competence building and more interdisciplinarity than short term projects. The industry's employees expand their professional competence and network through the program and by that strengthen the industry's competitive position. The SFI Metal Production has served as a professional resource for problem solving and technical discussions. The Centre constitutes a starting point for new project ideas that form the basis for spin-offs both internally and externally. The Centre has become an important meeting point for knowledge exchange and network building – activities that will continue also after the SFI period. The Centre has been actively seeking additional funding to ensure self-sustainability beyond the duration of the Centre. Sources of research funding are RCN and EU Horizon 2020. Until today, the SFI environment has received funding for 11 EU funded projects and 25 projects funded by RCN and four INTPART projects. The total associated project portfolio has reached 1,5 billion NOK.

SAMMENDRAG
RESULTATER 2015 - 2023

Metaller har stor betydning for vårt moderne dagligliv, bl.a. i mobiltelefoner, utstyr for produksjon av fornybar energi som vindmøller, solcellepaneler og batterier. Fremtidig produksjon av metaller vil kreve bærekraftige prosesser uten utslipp av CO_2, med effektiv utnyttelse av både energi og materialer - "doing more with less". Norsk metallurgisk industri har i dag verdens laveste CO_2 foravtrykk da produksjonen er basert på fornybar elektrisk kraft, og svært effektive prosesser. Karbon er fremdeles et nødvendig råstoff i metallproduksjon, så det er foreløpig ikke mulig å unnslippe utslipp av CO_2 totalt.

Senterets visjon er «ressurseffektiv metallproduksjon fra en ren industri», noe som reflekterer industriens fokus i 2013 – men en visjon som fortsatt er gyldig med reduksjon i utslipp av CO_2 og en mere effektiv bruk av materialer og energi.

Det er nødvendig med mer kunnskap om kjerneprosessene for å løse fremtidens utfordringer i industrien. Som et resultat av dette, er de primære målene for senteret å gi industrien tilgang på verdensledende fundamental kompetanse og kandidater, styrke innovasjonsevnen til industripartnerne, og etablere en samarbeidsplattform for metallproduserende industri i Norge.

Vertsinstitusjon for senteret er NTNU, senterleder er Aud N. Wærnes fra SINTEF. Forskningspartnere er SINTEF Industri, SINTEF Energi og NORCE, og bedriftspartnere Hydro, Alcoa innen produksjon av aluminium, Elkem, Finnfjord og Wacker Chemicals Norway innen produksjon av silisium og ferrosilisium, Eramet innen produksjon av manganholdige ferrolegeringer og Eramet Titanium & Iron innen produksjon av TiO_2 råstoff til pigment og råjern. REEL er leverandør av utstyr primært til aluminiumindustrien.

Det er skrevet et høyt antall publikasjoner i SFI Metal Production. Målet for senteret var å publisere 50 journalartikler og 70 konferansebidrag. Senteret har nå mer enn doblet dette antallet, med 150 journal artikler og 180 konferansebidrag. Det er skrevet tre bøker i senterperioden, og senteret har bidratt med kapittel til ytterligere to bøker. I tillegg er det skrevet mange tekniske rapporter.

Forskere fra senteret har mottatt flere priser for det vitenskapelige arbeidet på SFI Metal Production. Dette gjelder spesielt priser for beste foredrag/poster og utnevnelse som ordstyrer på internasjonale konferanser.

Betydningen av SFIen for industrien har vært betydelig. Det er gitt tre lisenser på pragmatisk modellering mellom en forskningspartner og en industribedrift, to innenfor aluminium med Hydro og Alcoa, og en sammen med Eramet innenfor manganlegeringer. I tillegg ble det i 2021 etablert et Spin-Off selskap som har utviklet teknologi for sensorer som måler støvinnhold. Visualisere fordelingen av støvpartikler i f.eks. en industrihall.

Medlemmene av SFI Metal Production har vært attraktive som bidragsytere i ulike offentlige utvalg som f.eks. Prosess21 som skal gi råd og anbefalinger om hvordan Norge best kan redusere utslipp fra prosessindustrien i 2050 og samtidig legge til rette for at virksomheter i prosessindustrien har bærekraftig vekst. Strategiarbeidet ble initiert av Næringsdepartementet i 2018.

Senteret har etablert relevant forskningstrening for studenter og forskere. Doktor- og masterstudenter har arbeidet i senteret i tett samarbeide med industrien. I tillegg til vanlige fag, er det arrangert som er en blanding av generelle presentasjoner relatert til individuelle prosjekter, generelle tekniske tema og ikke-teknologiske tema som forskningsetikk. Senteret har organisere grupper av studenter og forskere som arbeider på samme faglige område med ulik tilnærming, med stor suksess. Relevant forsker trening bidrar med interessante og høyt kvalifiserte kandidater tilgjengelig for rekruttering av industrien.

SFI Metal Production har en utmerket Fagkomite av anerkjente medlemmer fra internasjonale akademiske miljø og industri som har bidratt til den faglige utviklingen av senteret.

SFI Metal Production er en hjørnestein når det gjelder forskning innen metallurgiske prosesser i Norge, og er blitt en synlig europeisk node. Senteret har fått innvilget fire søknader til «International partnership for excellent education, research and innovation, INTPART». Det overordnede målet med prosjektene har vært å etablere og utvikle et langvarig samarbeid mellom NTNU, SINTEF og NORCE med universitet i Sør-Afrika, Japan, Sør-Korea, Canada vedrørende forskning og høyere utdanning.

Det har vært mange internasjonale gjesteforskere tilknyttet senteret. Disse er viktige for utveksling av ideer og informasjon om den internasjonale utviklingen på forskningsfronten. Forskere fra NTNU og SINTEF utviklet en ide sammen med forskningsmiljøet i Sør-Afrika, som senere ble til et EU-finansiert prosjekt, PREMA-Energy efficient, primary production of manganese ferroalloys through the application of novel energy systems in the drying and pre-heating of furnace feed materials.

Forskere fra SINTEF og NORCE har vært veiledere for mange av doktor- og masterstudentene i senteret. Senteret har oppmuntret studentene og forskerne til å skrive vitenskapelige så vel som populærvitenskapelige publikasjoner.

Et senter med åtte års levetid, gir tid til en mere dyptgående forskning, kompetansebygging og mere tverrfaglighet enn kortsiktige prosjekter. Ansatte i industrien utvider sin faglige kompetanse og nettverk gjennom deltakelse i SFI programmet og bidrar derved til å styrke industriens konkurranseposisjon. SFI Metallproduksjon har fungert som en profesjonell ressurs for problemløsning og tekniske diskusjoner. Senteret utgjør et utgangspunkt for nye ideer som danner grunnlag for Spin-Off prosjekter både internt og eksternt. Senteret har blitt et viktig møtepunkt for kunnskapsutveksling og nettverksbygging, aktiviteter som også vil fortsette etter senterperioden.

Senteret har aktivt søkt ytterligere finansiering for å sikre bærekraft utover senterets varighet. Kilder til forskningsmidler er RCN og EU Horizon 2020 and Horizon Europe. Fram til i dag har SFI-miljøet mottatt midler til 11 EU-finansierte prosjekter og 25 prosjekter finansiert av RCN inklusive fire INTPART-prosjekter. Den totale tilhørende prosjektporteføljen for senteret er nå på 1,5 milliarder NOK.

OUR VISION AND OBJECTIVES

Vision: ***Resource efficient metal production from a clean industry***

The SFI Metal Production is within an area where the Norwegian research community and industry partners, have an international leading position. Today, the Norwegian metallurgical industry has the lowest CO_2 footprint in the world due to a production based on hydropower, and very efficient processes. The Centre Vision is "Resource efficient metal production from a clean industry". As such, the Centre's vision reflects the status and goals of all industrial partners.

With the Centre vision the overall SFI **objective** is creating a basis for industry innovation. The Centre has interpreted "creating a basis for industry innovation" as:

1. Establishing fundamental knowledge (competencies) – "measuring things". Through these activities the Centre builds scientific excellence
2. Strengthening our collaborative networks nationally and internationally
3. Educating candidates and cultivating the integrated pattern of human knowledge, belief, and behaviour that increase the capacity for learning and transmitting knowledge to succeeding generations
4. Bringing forward new ideas that can be further developed outside/in collaboration with the Centre
5. Being a "think-tank" and meeting place for industry and research across sectors

THE **PRIMARY OBJECTIVE** OF SFI METAL PRODUCTION IS TO:

- *Strengthen the innovation potential of one of Norway's largest land based industry*
- *Give access to world-class fundamental competence and candidates*
- *Be a collaboration platform for the Metal Producing Industry, Academia and Research communities in Norway*

THE RESEARCH HAS BEEN DIVIDED INTO

FIVE MAIN RESEARCH DOMAINS, RD

The Vision has been unchanged during the Centre Period reflecting the need for more competence and innovation in the industry in order to solve future challenges. The objectives in the Research Domains, have changed for some of the RDs reflecting the need for activities that harmonies better with the change in focus for the industry during the Centre period.

These are the specific objectives that have been the basis for the RDs. A thorough description of changes made in scientific objectives on a RD level, is described in the chapter Research Results.

RD1: FUNDAMENTALS AND MODELLING TOOLS

In the Centre, RD1 is related to complementing experimental research activities with models of appropriate complexity. The overall aim is to enhance the understanding of industrial phenomena, strengthen experimental research advances, and facilitate innovation activities in the industry.

Research Objectives

- Evaluate systems for experimental data useful across various software platforms and, if appropriate, establish this as a tool for the researchers.
- Explore and implement scientific computations to support and enhance research activities.
- Developments within aluminium production: Understand the dissolution properties of alumina.

RD2: PRIMARY METAL PRODUCTION

RD2 aims to develop fundamental knowledge and competence to support industrial innovations for the next generation metal production processes.

Research Objectives

- Develop a concept for a step-change process in silicon production that will reduce energy consumption and CO_2 emission: Identify the inhibitors and catalysts in the Si production reaction.
- Develop a step-change process in SiMn production that will reduce the energy consumption and CO_2 emission: Identify the inhibitors and the catalysts in the SiMn production reaction.

RD3: RECYCLING AND REFINING

In refining and recycling of metals, the behaviour of impurities is the main focus. In RD3, increased knowledge of the thermodynamics and kinetics of oxidation-, refining- and waste utilisation processes, is the overall objective.

Research Objectives

- Improve filter properties and filtration technology
- Development of the thermodynamic and kinetic basis for Si refining.
- Identify the effect of minor/trace/alloying elements on aluminium oxidation
- Understand dross formation and handling in order to develop sustainable dross treatment.
- Recovery of metallurgical by-products and wastes, with or without residual metal content.

RD4: EMISSIONS AND ENERGY RECOVERY

Implementation of new and innovative solutions for energy recovery and reduced emissions require fundamental knowledge of process emission formation and of the dust and fume properties. To reduce gaseous and dust emissions, in-situ and on-line measuring methods will be used or developed to understand the effect of operational strategies and process variations beyond state of the art.

Research Objectives

- Develop a fundamental understanding of the mechanisms and challenges for enhanced energy recovery in Al electrolysis and Ferroalloy production.
- Develop the knowledge base of the relation between emission formation, emission discharge, spreading and emission avoidance.
- Development of measurement methods, standards and tools to enable emission control.

RD5: MATERIALS AND SOCIETY

The main aim of RD5 is to increase the public awareness of metal production and its benefits in a modern society.

Metals are an integral part of a wider system that encompasses all aspects of modern society. This Research Domain has a special responsibility to identify opportunities and disseminate research aspects that can contribute to the understanding of the social value of metals and how they can support a sustainable development of society.

Research Objectives

- Material Flow Analysis and Life Cycle Thinking
- Industry networking and recruitment
- Exchange of best practices for industrial innovation

PARTNERS

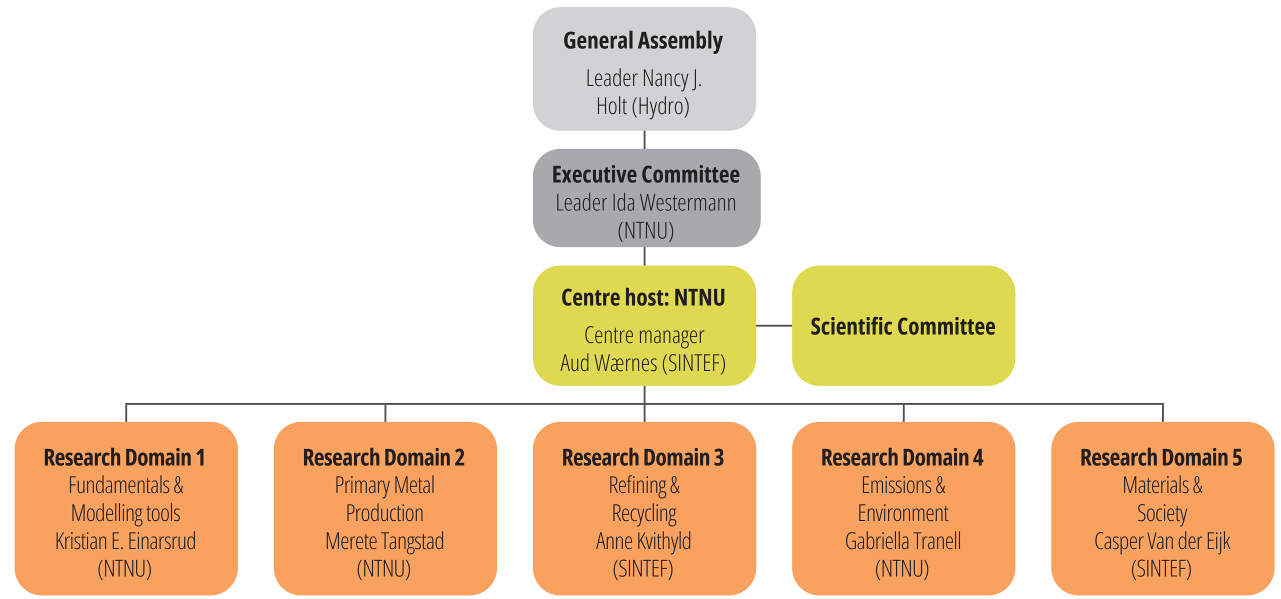
RESEARCH PARTNERS:

SINTEF NTNU NORCE

USER PARTNERS:

WACKER FINNFJORD Alcoa Hydro Elkem eramet eramet Titanium & Iron

ORGANIZATION



SFI Metal Production is hosted by Department of Materials Science and Engineering, NTNU and the Centre manager is Aud Nina Wærnes (SINTEF).

General Assembly (GA): All industry partners and research partners are represented in the GA. Nancy J. Holt (Hydro) has been chair of the GA since 2021. The other members of the GA are: Ketil Rye (Alcoa), Anders Sørhuus (Reel Norway AS), Haavard Elstad (Eramet Titanium & Iron AS), Benjamin Ravary (Eramet), Marit Dolmen (Elkem), Torbjørn Halland (Wacker), Erlend Olsen (Finnfjord), Ida Westermann (NTNU), Nina Dahl (SINTEF Industry), Petter Nekså (SINTEF Energy), Ulrik Thisted (NORCE), Oddvar Gorset (The Research Council of Norway, RCN).

Executive Committee (EC): Ida Westermann (NTNU) has been the chair of the EC since 2022. The other members of the EC are: Nancy Holt (Hydro), Ketil Rye (Alcoa), Benjamin Ravary (Eramet), Marit Dolmen (Elkem), Eli Aamot (SINTEF), Ulrik Thisted (NORCE), Oddvar Gorset (RCN).

The Centre management and work package leaders: Aud N. Wærnes (SINTEF) is the director of the Centre and Kari Håland is the administrative coordinator. The five Research Domain (RD) leaders are also part of the management team. The last years of the Centre period the RD leaders have been: Kristian Etienne Einarsrud (NTNU), Merete Tangstad (NTNU), Anne Kvithyld (SINTEF Industry), Gabriella Tranell (NTNU) and Casper Van der Eijk (SINTEF Industry).

The Scientific Committee (SC) is our independent body of leading academic experts providing an objective view with respect to the scientific quality of work planned/carried out. The members of SC are:

Professor
Markus A. Reuter
Helmholtz Institute Freiberg for Resource Technology

Professor
Margaret M. Hyland
University of Auckland and Ministry of Business Innovation & Employment

Professor
In-Ho Jung
Seoul national University, South Korea

Professor Emeritus
Jean-Pierre Birat
Secretary General chez ESTEP, CEO IF Steelman

Location: SFI Metal Production is located at NTNU Gløshaugen in Trondheim, third floor in "Bergbygget" at Alfred Getz vei 2. SFI members from industry, SINTEF and NTNU are working side by side, enabling close interaction and collaboration between the partners.

Executive Committee meeting spring 2022

How we cooperate within the Centre

The management team have met every second week to plan and organize the Centre activities. The Research domain leaders (RDLs) have been responsible for developing the Annual Work Plans in close cooperation with the industry and the research partners. The RDLs have coordinated on a day-to-day basis the progress and made sure the deliverables agreed upon are produced. Furthermore, they have been responsible for following up decisions made by the EC and GA.

In order to stimulate innovation processes, the industry partners have been challenged to look for results that have a potential for future innovation in the metallurgical industry. The EC has operated as the Innovation Committee for the Centre. The biannual consortium meetings (Spring- and Autumn Meetings) have been important arenas for knowledge sharing and discussion on scientific results with potential for application in the industry.

The co-location of research and industry partners has been an advantage and facilitated close collaboration. Throughout the Centre period there have been regular visits to user partners, campaigns and personnel mobility that have stimulated the development of scientific activity highly relevant to industry.

RESULTS

HIGHLIGHTS FROM THE RESEARCH DOMAINS, 2015-2023

From measuring campaign at Thamshavn, to identify the gas and dust composition from the tap hole. The picture shows a test with a gas shielded towards the tap hole. Photo: Svend Grådahl, SINTEF

RD 1

FUNDAMENTALS AND MODELLING TOOLS

BY RESEARCH DOMAIN LEADER KRISTIAN ETIENNE EINARSRUD, NTNU

Original research plan and development of research plan

The original objectives of Research Domain 1 (RD1) – Fundamentals and Modelling Tools – was to combine existing and new data in an easily accessible and user-friendly format and to develop and demonstrate generic, standardized frameworks for coupled scientific computing. Following a re-organization of SFI management in 2019/2020, activities relating to alumina dissolution were moved from RD2 – Primary Metal to RD1, owing to extensive modelling activities within this subject. As the activities have progressed, it has become evident that user cases were more important and more easily understandable for the users, than generic frameworks, and as such the activities within RD1 were focused towards more specific problems and cases, exemplified by coupled simulations applied to formation of NOx and SiO_2, coupled simulations for SiMn production and atmospheric dispersion modelling for Al- and FeMn industry. While the activities were focused towards specific processes and industries, they were presented to the full consortium, allowing for partners to learn the methodologies and propose extensions and new user cases to which the methods could be applied.

Research achievements

The research within RD1 has mainly evolved around two axes, one related to fundamentals and modelling in general and one relating specifically to the dispersion and dissolution of alumina powder in cryolite melts, a key step in the production of primary aluminium. The research has been documented in 15 peer reviewed publications (with 5 more pending review/final publication), 20 technical reports and more than 80 technical presentations in various forms, including conferences such as the TMS Annual meeting and The International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries, as well as industrial workshops. The activities have been a close collaboration between industry, research institutes and academia, resulting in research based education and training of 6 BSc students, 10 MSc students, 3 PhD candidates and 1 Post Doctoral fellow. Selected highlights from the activities in RD1 are given in the following.

Highlights of scientific results

Alumina - aluminum oxide - is the raw material used to produce primary (non-recycled) aluminum metal. The production takes place in an energy-intensive electrochemical process where alumina powder is added regularly and dissolved into a molten bath where the reactions take place. Feeding, dispersion and dissolution of the powder is critical to ensure an optimal distribution of the raw material in the process, which in turn contributes to lower emissions of greenhouse gases and higher energy efficiency. Experimental campaigns have revealed that the powder is not dissolved immediately but forms a “raft” that delays further dissolution. The rafts are porous and consist of (unreacted) powder and frozen bath with varying chemical composition, affected by different operating conditions (temperature of molten salt and raw material, flow conditions) and qualities of the raw material (amount of fines, amount of contaminants such as fluoride).

In parallel with experimental measurements, extensive modelling work has been realized, considering phenomena on both the scale of single alumina particles and up to industrial conditions. The modelling on

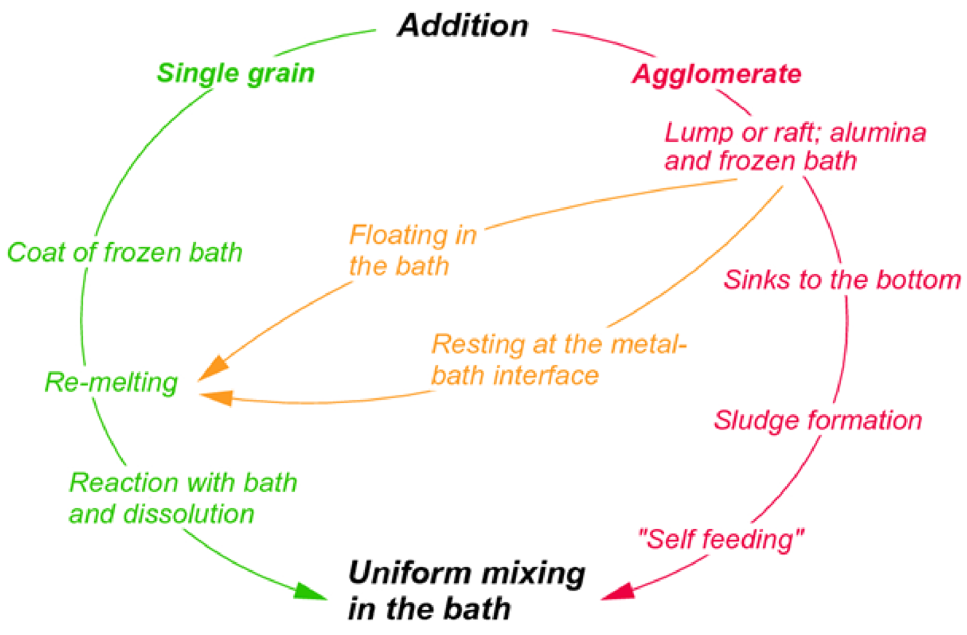
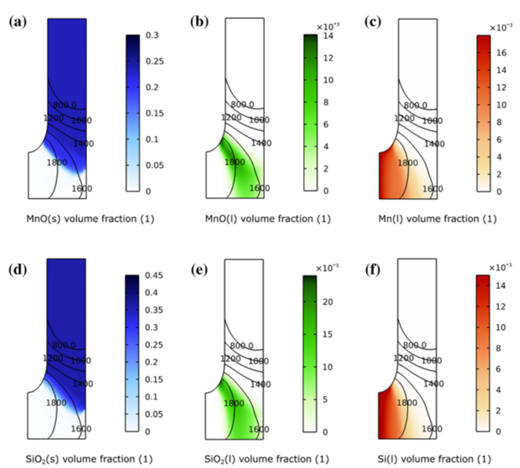


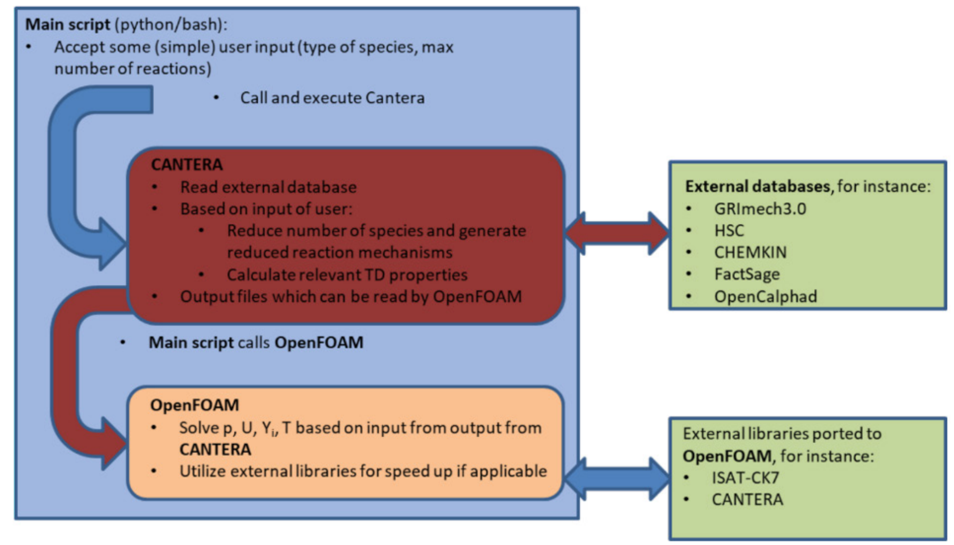
Illustration of possible paths for alumina dissolution. (Skybakmoen and Solheim: Mass- and Heat Transfer During Dissolution of Alumina. Light Metals 2020)



Sample distribution of oxide and metal phases in SiMn furnace (Sparta et al.: An overall furnace model for the silicomanganese process. JOM 2021)

industrial scale has been realized through a so called pragmatic computational framework, which allows for predictions of alumina- and temperature distribution 50-500 times faster than real time, and thus lays an important fundament for future development of digital siblings.

Ferroalloys are produced in arc furnaces where ores containing the sought metals react with carbonaceous materials. The ore contains various metal oxides and the process must be controlled both in terms of chemistry and temperature in order to only produce the sought metal phases. Unwanted metals are removed from the furnace in the form of slag.
Due to the process complexity, computer models are commonly restricted to for instance electrical conditions, thermal conditions, or chemical reactions. Based on pilot scale experiments, a first of its kind comprehensive model for silicomanganese furnace has been developed, which simultaneously considers electrical and thermal conditions, process chemistry, and flow of solid and liquid substances. The model provides new knowledge of the inner state of the furnace and



Overview of coupled thermodynamic-kinetic-fluid-dynamic simulation framework.

predicts and explains for instance observed increases in temperature during over-coking as well as associated changes in product composition.

In general terms, metallurgical processes involve a number of simultaneous phenomena related to chemistry, thermodynamics and flow. The processes often take place at high temperatures and with highly reactive materials, which makes direct measurements challenging. Mathematical models are often used to increase understanding of the process and to determine parameters that cannot otherwise be measured. Traditionally, this is done by separate studies of relevant parameters, which can result in the loss of critical information arising from coupling between different phenomena, e.g., flow models tend to assume thermodynamic equilibrium. Open source software, in force of being open, and thereby customizable, and thereby customizable, allows for different models and approaches to be coupled in new ways. A framework based on OpenFOAM (fluid dynamics), CANTERA (kinetics) and ChemApp (thermodynamics) has been developed and demonstrated for the formation of NOx, SiC and μ-SiO_2, highlighting some of the possibilities which novel simulation strategies can offer.

Awards
Current RD leader Kristian Etienne Einarsrud was awarded the TMS 2019 Young Leader in Light Metals award at the TMS 2019 Annual Meeting in San Antonio, Texas. He was later appointed session chair within alumina dissolution for the TMS 2020 Annual Meeting in San Diego, California and subject chair in Aluminium Reduction Technology for the TMS 2022 Annual Meeting in Anaheim, California, mainly based on activities and results achieved though SFI Metal Production.

PRIMARY METAL PRODUCTION

BY RESEARCH DOMAIN LEADER MERETE TANGSTAD, NTNU

Original research plan and development of research plan
The long-term objective for Research Domain 2 was to develop fundamental knowledge and competence to support industrial innovations for the next generation processes. RD2 hence focused on reaction mechanisms in both the high temperature production of metals, which are the metal producing processes, as well as the low temperature area, that is gas-solid reactions. The research plan was divided in two main areas. The first one was to find experimentally, and then model, reactions and reaction rates for metal producing reactions. The next part was to determine the effect of raw material properties on operational parameters like energy consumption and CO_2 emissions.

The research plans were divided in the following areas:
Metal producing reactions: The metal producing reactions for ferromanganese, silicon and aluminium were studied. This was done both from a chemical view (reaction mechanisms, thermodynamics, kinetics) and from an electrical viewpoint (current paths and energy distribution in the furnaces /cells). In this part also the production of TiO_2 slag is included.

Raw materials: There is a large variation in the raw materials for these processes. The focus was on prereduction and pretreatment of manganese ores, effect of quartz and production of alumina. Later agglomerates both in the Mn-and Si/FeSi-industry were developed and/or characterized.

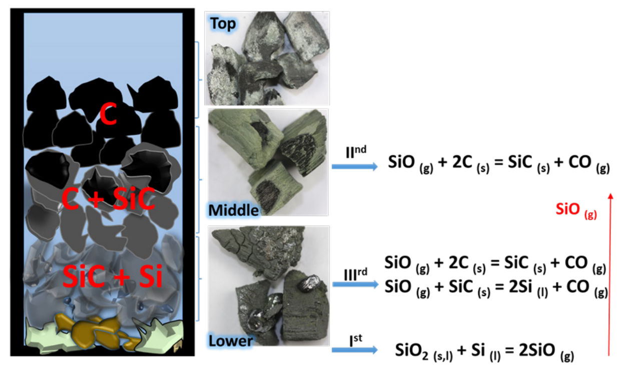
Method development: The development of equipment measuring the electrical properties in the Al-cell, the competence building of using a two-zone furnace for e.g. Si-production, and enhanced knowledge of pilot scale operation were the main task in method development.

Technology transfer to the partners has also been an important part of the research plan.

The research plan was adapted to the changing times. It was seen quite early in the SFI that the financial resources available was limited and hence it was decided, in agreement with the partners, to focus more on the metal producing reactions and less on the raw materials. Secondly, due to practical reasons the aluminium was moved to RD1 after a couple of years. Finally, the urge towards a carbon neutral production changed quite dramatically during the SFI period. The focus on biocarbon and the use of H_2 was therefore increased within the research areas of the RD2.

Research achievements
The research activities in RD 2 have been conducted in collaboration with international partners from South Africa (MINTEK and Northwest University), Japan (University of Tokyo) and China (University of Science and Technology in Beijing). Brazil has also been a cooperative country with 2 PhD-candidates as exchange students at NTNU, in addition to a MSc student. The Norwegian research partners NTNU, SINTEF and NORCE have been strongly participating in RD2. There have been 3 PhDs and 2 Postdocs pushing the knowledge front for the industry as well as for the research partners. 16 MSc students have been working for this RD. The results have been published in journals and conferences (63), in a number of internal reports as well as in meetings with the industry and seminars. Projects have emersed from this Research Domain like KPN Controlled Tapping, KPN Reduced CO_2, IPN HighTemp Quartz, KPN BioMet, EU Horizon 2020 PreMa. Selected highlights from activities in RD2 are given in the following.

Highlights of scientific results
High temperature reactions in the Mn- and Si/FeSi-furnaces:
The first area where the knowledge front has been pushed is the reaction mechanism where SiMn is produced from manganese ores, quartz and carbon. The rates of reaction were surprisingly seen to be in two steps, first a slow step followed by a fast step. The first step was catalyzed by small amount of sulfur and could be completely removed when enough sulfur was present. This means that the reaction mechanism will be very different if Mn-ores or HC slag are used. The second area mentioned here is the reactions in the Si/FeSi furnace. The SiC formation is seen to go through two paths at high temperatures. First at both low and high temperature, the walls in the carbon material will be transformed to SiC. At higher temperatures some SiC will be formed additionally through a gas phase reaction. The β-SiC will again either transform to α-SiC or to liquid silicon. The transformation to α-SiC was seen to occur above 2100 °C. The liquid silicon can be formed from 1750 °C in the β-SiC particles, and this can start quite high in the furnaces.



The third area regards the electrical resistivity of materials in the Si/FeSi furnace during heating. The electrical resistivity of the materials in the furnace will decide where the energy is developed and is hence one of the most important operational parameters. The carbon materials in the furnace will gradually transform to SiC, which again will start to produce Si in the pores as mentioned above. The electrical resistivity of partly transformed material was before this project unknown. Through a PhD and 2 MSc project we now have determined the electrical resistivity of partly transformed materials. When C is transforming to SiC the resistivity will increase, however when the Si is starting to form, the resistivity will again decrease. When a mix of raw materials is used, like various carbon materials and quartz, the resistivity will be decided by the amount of the most conductive carbon material. It is also seen how the condensate makes the charge insulating.
Another important activity conducted is the study of production of TiO_2 slag. The study of the dissolution of ilmenite sand and pre-reduced ilmenite pellets in titania slag shows that the former dissolve faster at comparable conditions. The pellets will undergo a fusing stage accompanied with the release of metallic iron; such stage is not observed for sand material.

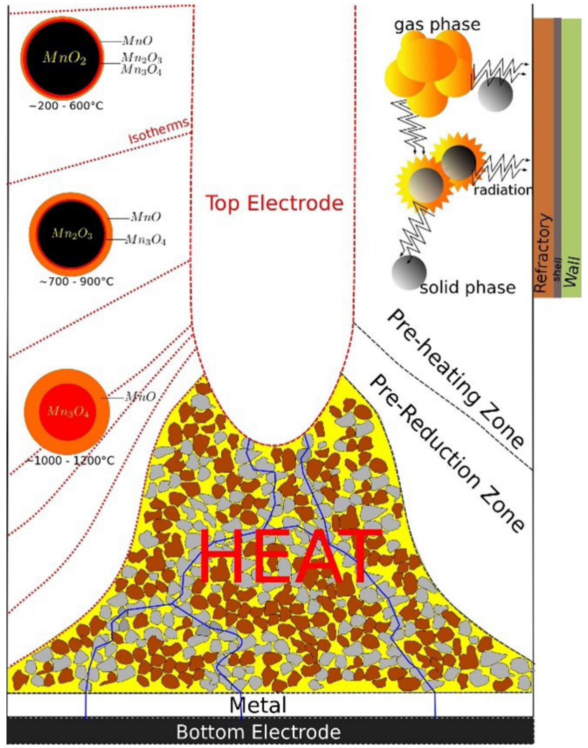
Raw materials
One of the large subjects has been to determine the properties of carbon materials, and especially to compare the fossil carbons to bio-carbons. In SiMn it has been seen that coke reacts faster than charcoal when using ores, however charcoal will be faster when high S materials like HC slag is used. One of the reasons for this may be due to an increased wettability when S is present. In Si/FeSi production it is verified that charcoal transforms faster than fossil carbon materials to β-SiC, this is due to the structures of the charcoal, with lower density, that has a higher amount of pores as well as thinner cell wall thickness. It was also found that β-SiC transformation to α-SiC transformation was faster using charcoal versus fossil sources. Finally, it was seen that Si was produced faster in β-SiC from charcoal versus fossil fuel. The electrical resistivity of partly transformed charcoal was also higher than the fossil fuels, so in the end, biocarbon is very beneficial for the industrial

operation in many ways. The main disadvantage using charcoal is the low strength and low density.

Technical solutions for carbon neutrality, not only biocarbon, has been a major concern but also the use of hydrogen in the Mn-production. It was seen that small amount of H_2 in the CO/CO_2 gas would prereduce the Mn-ores faster than CO/CO_2 gas. Using 100% H_2 would increase the reaction rate of the Mn-oxides, increase the decomposition of the carbonates, and it reduced the iron oxide to metallic iron at lower temperatures than CO gas.

The use of agglomerates made from waste materials will also be an increasing issue in the future. Industrial made Mn-raw material briquettes were studied regarding prereduction and melting, and the best composition to use industrially was recommended. Waste materials from Mn-ore tailing dams was also briquetted and studied, and one of the results indicated that carbon in the briquettes was not reacting until the higher manganese oxides was prereduced to MnO. This signifies that even in the Mn-industry composite briquettes of ore and carbon may be used without increasing energy- and carbon-consumption. In cooperation with a Brazilian university, FeSi composite briquettes were also made, and a recipe of production method (binders and pretreatment) was proposed based on the best briquettes. The use of agglomeration of waste material will be continued in KPN BioMet.

New methods
A number of scientific methods have been developed during the SFI period. Methods for measuring electrical resistivity at high temperatures have been developed. A procedure of pilot scale experiments was developed. The pilot scale experiment was also used to develop a mathematical model calculating the main feature of the process. This model has later been used in other projects that include the industry. An app calculating the slag properties was also developed and is shared with the industry. A one-of-a-kind two zone furnace was purchased in the project. This furnace allows for one gas developed at one temperature, mixed with raw materials at another temperature.



Technology transfer
The competence building of the partners was done through reports/papers, common seminars, webinars and courses. Two-days Mn- and Si-courses with the industry were organized annually and a carbon- and HSC-course was organized once. The courses were offered to students and industry.

Awards
MSc student Trine Asklund Larssen won the price for excellent poster at the TMS 2017 in San Diego. The title of her poster was Reduction of MnO and SiO_2 from Comilog based Charges.
Vince Yves Canaguier won the prize "Most viewed presentation" at Molten Slag, Fluxes and Salts 2021 (Digital conference).

RECYCLING AND REFINING

BY RESEARCH DOMAIN LEADER ANNE KVITHYLD, SINTEF

Original research plan and development of research plan
In Research Domain 3 - Recycling and Refining - controlling impurities is a key. Unwanted elements may affect our ability to recover materials for new uses. Moreover, removing impurities through refining steps have thermodynamic and physical limits. Fundamental understanding of the interaction of molten metal with various elements with solids, gases and slags has therefore been the core of RD 3. In addition, new technologies for recycling and recovery of waste products have been examined.

Research Domain 3 was originally divided into three overall areas:

- Oxidation of metals
- Molten metal purity
- By-products and waste streams

Oxidation of aluminium got a head start as a PhD candidate was hired soon after the Centre opening. This activity was continued by yet another PhD student. Various studies of aluminium oxidation were also performed extensively by SINTEF, the Centre industrial partners, and other international aluminium companies and suppliers.

In refining, two techniques were studied in detail, each of which also had associated PhD candidates. Oxidative ladle refining of metallurgical grade silicon was one topic, the other was characterisation of ceramic foam filters for aluminium.

An overview of solid waste and by-products in the metallurgical industry in Norway was compiled together with RD 5. Efforts were made to select a by-product/waste study by the Metal Production Centre for the final years. Dross was finally chosen as the by-product with the highest research and value potential. Hence, a Post Doc on dross was engaged for 2 years.

The importance of resource conservation through maximizing the yields and new products from by-products and waste streams became more evident in the last period of the Centre. Smaller projects on topics such as surplus bath, spent potlining and end of life packaging were started in the Centre to address these challenges.

Early in the Centre period the need to update the classical book "Principles of Metal Refining" from 1992 and to include more on recycling, silicon, and new processes was evident. The update required more work and efforts than initially presumed, but the book was finalised in the Centre period.

Research achievements
The research activities in RD 3 have actively collaborated with international partners and companies outside the Centre such as Constellium, Gränges, Metallco, Novelis, Real Alloy, Trimet, Linde Gas, and DTE. The work within RD 3 has been used as input for establishing new projects (e.g. BadeLand, SiSAl, and Alpakka). The RD has hosted and been invited to international workshops. The researchers have also been very active at organizing and presenting at the TMS Annual meetings as well as in webinars and student/industry seminars. Visiting Master and PhD students from Italy, Belgium, India, USA, and Iran have been supervised along with 15 Norwegian Master students, 4 PhD candidates and 2 Postdocs.

Selected highlights from the activities in RD3 are given in the following.

Highlights of scientific results

Oxidation

The work on fundamental understanding of oxidation of aluminium started with investigating the effects of Be. Small-scale experiments on AlMg alloys showed that while 2 ppm Be inhibits oxidation, it does not affect the strength of the oxide skin. It was later concluded that the beryllium forms a thin continous dense layer below the oxide that prevents the transport of magnesium through the surface, and thus inhibts the oxidation. Our study is the first scientific approach to explain the protective mechanism Be provides. Further investigation focuses on alternative additions to the aluminum melt (e.g. Ca and Sr). This surface phenomena was studied in more realistic surface to volume ratios through a large-scale experimental set-up. The latest addition in new equimpment is a Laser-Induced Breakdown Spectoscopy (LIBS) shown in picture to the left. The study with LIBS on oxidation shows that adding Sr and Ca reduced the Mg partial pressure above the melt surface.

The Laser-induced breakdown spectoscopy (LIBS) used in the investgation of oxidation of molten aluminium.

CO_2 in the atmosphere has previously been shown to cause a reduction in the oxidation. Studies in the Centre showed that additions of as little as 5 % CO_2 to air was able to delay breakaway oxidation in AlMg alloys. Small-scale studies were further used to investigate the oxidation of AlMgSi alloys. An amorphous C-C layer on top of a nanocrystalline MgO layer was detected, for the first time, for both high and low Mg containing alloys. The effect of water vapour, N_2, and O_2 in combination with CO_2 have also been thorougly investigated in the industrial facilities as their atmospheres are difficult to reproduce in our labratories. Also in this cases, only a small portion of CO_2 was sufficient to markedly reduce the oxidation of Al-Mg alloys.

Molten metal purity

Refining, either by gas purging or filtration, has significant impact as a basis for producing a metal with less impurities, hence resulting in improved metal quality. Reliable data to predict and understand the refining of molten silicon is key to improve the quality of molten silicon. The fundamental work on oxidative ladle refining described three primary steps: Initially, surface oxidation is the most prominent refining effect, resulting in a high calcia SiO_2-CaO-Al_2O_3 slag. Secondly, when the ladle reaches a critical fill height, slag formation by gas purging becomes the prominent refining effect. This results in the subsequent formation of new SiO_2-CaO-Al_2O_3 slag dominating the refining process. Third and finally, a critical amount of slag has been formed by gas purging and amassed in the ladle. An equilibrium between the bulk SiO_2-CaO-Al_2O_3 slag and alloy is approached by mass transfer of Ca and Al, both to and from the slag.

In 2017, characterisation of ceramic foam filters (CFF) for aluminium was given special study. The evaluation of the filtration efficiency of CFF using a water hydraulic system led to an empirical model to calculate pressure drop. The effect of eddies on re-entrainment of captured particles must also be considered.

By products and waste stream

"No waste" and "Value added by-products" are crucial to set a direction for future metal production. This was the common understanding between the metal producers and education/research at the first by-products/ waste workshop in 2016. Further, dross was selected as the main case for study. Dedicated workshops for dross were facilitated.

Picture from the International Dross and Packaging Recycling Workshop 15 - 16 May 2019 in Trondheim.

Characterisation of dross and proper sample taking are very important. Sampling tools and procedures to collect dross directly from the holding furnaces in the cast house were developed. Further, the possibility of physical separation of aluminium metal from the non-metallic compounds were addressed. Utilizing the separated metal for metallothermic reduction of MnO-containing slags resulted in process flexibility and energy evaluations for this new process. A new process to produce silicon using aluminium metal from dross for aluminothermic reduction of quartz in slag, is also pursued.

In dross treatment today, salt is used in a rotary furnace. Salt free dross processing in a plasma heated rotary furnace was tested and the resulting alumina evaluated for reuse in the electrolysis cell. Evaluations of salt versus salt free treatment of dross were tested in large scale, confirming that salt prevents dross formation.

Coalescence of the metal is important in the scrap and dross processing. The Centre has shown that correct pre-treatment of scrap increases the coalescence. Collection of packaging containing aluminium has been investigated along with the quality and quantity of aluminium from municipal waste. Development of a method for delamination of laminated multi-material packaging by water at high temperature and pressure showed very promising results, including only minor oxidation of the aluminium.

Other waste streams have also been investigated. Using the first cut from spent potlining of electrolysis cells as a reduction agent in ferroalloys production has been an aim. How the various elements of the SPL distribute during treatment is described in a literature review and modelling report. The limited opportunities for reusing surplus bath from aluminium production is suggested to be recovered in sulfuric acid or aluminium sulphate.

Awards

Cathrine Kyong Won Solem received the Light Metals Subject award for her paper "Evaluation of the effect of CO_2 cover gas on the rate of oxidation of an AlMgSi Alloy in Light Metals 2020.

Are Bergin received the Light Metals Division poster award for "Conventional and low phosphorus ceramic foam filters - chemical reactivity and thermal stability" at TMS 2019.

Massoud Hassanabadi was awarded for his oral presentation "Characterization of alumina based ceramic foam filters (CFFs) by evaluation of permeability within the CFF Blocs" at INCAL 2019.

EMISSIONS AND ENERGY RECOVERY

BY RESEARCH DOMAIN LEADERS GABRIELLA TRANELL (NTNU) AND THOR ANDERS AARHAUG (SINTEF)

Original research plan and development of research plan
Implementation of new and innovative solutions for energy recovery and reduced emissions require fundamental knowledge of process emission formation and of the dust and fume properties. To obtain such knowledge, new and combinatory in-situ and on-line measuring methods are needed to understand the effect of operational strategies and process variations.

Research in Research Domain 4 was originally divided into three overall areas:

- Scaling/clogging phenomena in off-gas systems
- Dust formation, clustering and spreading
- In-situ gas measurements – tools, standards and process control

As a starting point for the work, it was decided to add one additional activity: the compilation of three review journal articles, describing the state of the art in knowledge and measurements of airborne emissions from Si, Mn and Al industries. These articles were prepared in the period 2016-2019.

The work in the scaling/clogging area towards the Al industry was carried out as planned with a PhD candidate in close collaboration with SINTEF. With the awareness of the role of sulfur in the off-gas for scaling, an activity on measuring acid dew point in the off-gas by SINTEF was introduced in 2020. This activity was very successful and led to further measurements at various industrial sites in Norway. In 2021/22, the aluminium work was complemented by work on scaling in the Si industry by a MSc student.

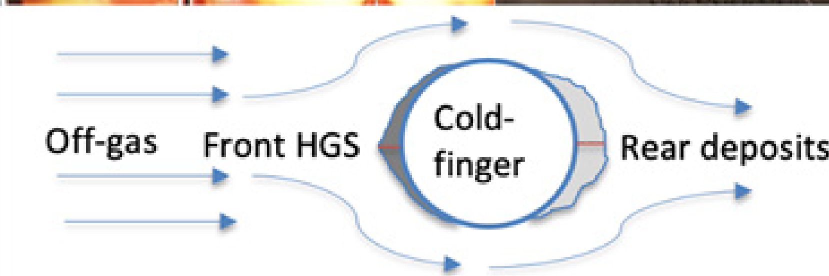
Under the heading of dust formation, clustering and spreading, the activity developed with time and included both fundamental mechanistic studies on Mn- Si and Al dust formation by a postdoc, a PhD candidate and two MSc students, as well as innovative research using cheap dust sensors to measure industrial dust emissions on-line. This technology was applied in both Mn, Si and Al industries. In addition, dust spreading models were developed by SINTEF and used to predict hall wind effects in-plant. Fence-line dust measurements by NORCE were also coupled up with other activities in the Centre.

In the in-situ-gas measurements area, PAH has dominated the work with a Postdoc and a PhD candidate, complemented with industrial VOC measurements by SINTEF. The use of "tubes" for gas sampling initiated in the Centre has opened up for more dynamic sampling possibilities. The activities on industrial PFC monitoring tapered off after 2019 as a result of the establishment of gas canister sampling and the fact that the Quantum cascade laser cost was too high for industrial investment for emission monitoring.

Research achievements
The work within RD 4 has been very diverse and agile and has nucleated new research areas, established new projects and an SME spin-off company for sensor-based dust measurements. The research activities in RD 4 have also collaborated actively and co-published with other projects and Centres (FME HighEff, KPN Controlled Tapping, RRP Ensense, IPN PAHssion). The research has been documented in 22 peer reviewed publications (with 4 more journal articles pending review/final publication), 7 memos /reports (not counting student theses) and a large number of technical presentations in various forms including conferences, such as the TMS Annual meeting and Infacon, 7 industrial workshops organized by the RD (3 scaling, 1 sulfur, 2 dust, 1 PAH) as well as webinars and student seminars. The activities have been a close collaboration between industry, research institutes and academia, resulting in research-based training of 3 MSc students, 3 PhD candidates and 2 Postdoctors. Selected highlights from the activities in RD 4 are given in the following.

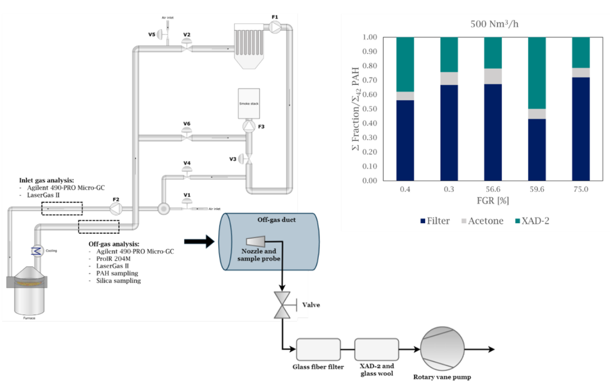
Highlights of scientific results
Scaling
Scaling in off-gas systems from different metallurgical production processes can cause problems in heat recovery systems and may sometimes be so severe that the whole exhaust system is blocked, and the operation must hence be stopped while blockages are removed. Off gases from aluminium electrolysis are complex and contain alumina particles together with various fluorine, sulfur, and carbon-containing gas components. In the PhD thesis by Daniel Clos a cold finger probe, simulating a heat exchange device, was placed in an electrolysis off-gas channel over periods of months, following the scaling dynamics. It was found that the scaling was close to linear with time and that scale, consisting of fine alumina particles and fluorine-based phases, built up on surfaces experiencing low gas flow-rates. Based on these findings, SINTEF has developed a new heat exchanger design which is aimed at high performance under strong fouling conditions.

Dust
Understanding fuming and dust formation mechanisms is key to being able to mitigate emissions. One of the main objectives in the fundamental work in the PhD work by Håkon Myklebust was to better understand the kinetics of fuming from FeMn/SiMn alloys. The mechanism behind fuming and oxidation/dust formation from such alloys is oxidation-enhanced evaporation of Mn. As such, the rate of fuming is a function of the kinetics of metal evaporation, determined by the alloy composition (activity of Mn) at the gas-liquid interface and the rate of oxidation (access to oxygen). For C-containing Mn alloys, the rate of de-carburisation of the metal in contact with oxygen is fast and as such, the fuming rate cannot be predicted based on the Mn-activity in the bulk composition of the alloy but is closer



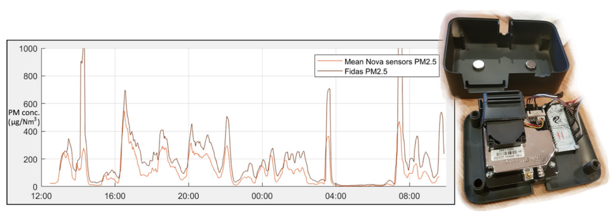
to that of a C-free alloy. At relatively modest oxygen flows over a liquid Mn-alloy surface, the evaporation rate is close to that in-vacuo.

The development and evaluation of using affordable but dynamic, spatially distributed, measuring systems for dust has been one of the more important achievements in the RD 4 research. Through a collaboration between NTNU and SINTEF, it was demonstrated through campaigns in both the Al-, Si- and Mn production industries that small portable sensor systems based on light scattering (nephelometer) can be effectively used to monitor the dust-load in the in-door environment of metallurgical industries. Simultaneous monitoring in many locations within the plant can both help to identify dust hot-spots, couple specific dust fractions to operations and understand the intensity variations over longer and shorter time periods.



Compilation of figures from Myklebust et al., JOM 2022

Gas Emission Measurements
It was early identified that there was a knowledge gap in both understanding the formation/ destruction of polyaromatic cyclic hydrocarbons (PAH) in different metallurgical processes and on how to best monitor/ measure the emission of these species. In the work of Postcoc (later SINTEF researcher) Heiko Gärtner, the first attempts of adapting sampling systems used in the aluminium industries to the ferroalloys industries were made. Realising the large scope of work needed to be undertaken, a new IPN project was initiated in parallel with the SFI Centre where sampling methodologies and strategies were a large part of the research work. In the SFI, PhD candidate Kamilla Arnesen studied the formation of PAH in the silicon production process in depth, particularly in a pilot system with gas recirculation together with PhD candidate Vegar Andersen in FME HighEff. Of particular interest was the large extent of 3- and 4-ring nitro-and oxy- substituted PAH species present in the off gas with high recirculation rates. The presence of sulfur-substituted PAH species was also studied in anode baking off-gases. It was shown that such species can be polar and may hence enter waste-water from off-gas cleaning if not effectively mitigated.



Compilation of figures from Arnesen et al. ACS IEC research, 2023

Awards
Thor Anders Aarhaug was appointed session chair for the PFC session at TMS 2017 in San Diego.

In 2020 Professors Gabriella Tranell and Jafar Safarian won The Sustainability award at the NV Faculty, NTNU, for their invention of the SisAl process, a process where silicon is produced with low environmental impact using secondary Aluminium and silicon raw materials.

Professor Gabriella Tranell for received Elkems Ærespris from Elkems Research Fund in 2021. Tranell received the award because of her broad research and contribution to the Ferrosilicon/Silicon industry.

MATERIALS AND SOCIETY

BY RESEARCH DOMAIN LEADER CASPER VAN DER EIJK, SINTEF

Original research plan and development of research plan
Research Domain 5 (RD 5) – Materials and Society – was initially established with several key objectives. The first of these was to systematically assess the flow of substances and materials, with a focus on resource consumption, product creation, and waste generation. While the primary focus was on the aluminium industry, the project expanded to include modelling of material flow in a ferrosilicon silicon plant. The second objective involved the collection of data related to production, energy use, and emissions within the Norwegian metallurgical industry. This data was compiled and published in multiple reports throughout the duration of the SFI Centre period. RD 5 also served as a platform for the development and testing of innovative concepts. A prime example of this was the research conducted on the Pedersen process, which culminated in a PhD degree and seven publications that have been cited over 150 times. The final objective was to contribute to the road map developed by the Process Industry. This involved identifying the primary innovations required in the industry, a task carried out by several key participants in the SFI Centre as part of the PROSESS21 strategic initiative coordinated by the Norwegian government.

Research achievements
Material Flow Analysis
Material Flow Analysis (MFA) is a methodology used to assess the flow and transformation of materials and substances through a system. It can be used to analyze the use of materials and resources in various industrial sectors and to assess their environmental impacts. MFA can be applied to resource efficiency and waste management, environmental assessments, sustainable development, and policy development. Overall, MFA is a valuable tool for understanding material flows and identifying opportunities for improving resource efficiency and reducing environmental impacts.

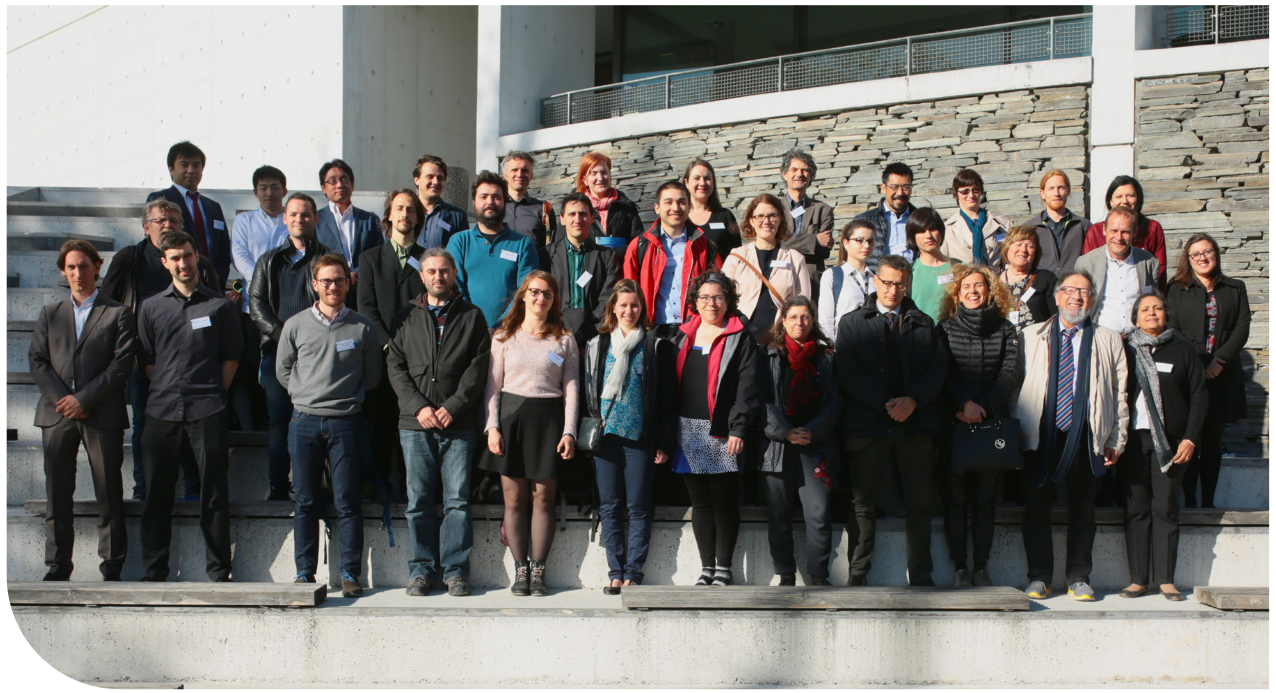
Romain Billy did his PhD within the SFI metal production. His thesis proposes the use of new tools for monitoring and simulating the future of metal cycles and their emissions at different scales, using the aluminium cycle as the main example for applications. The approach developed for monitoring material cycles is based on two main components: a framework for designing maps of the physical economy at the societal scale and a physical accounting framework to monitor material use and emissions of industrial plants based on the application of multilayer material flow analysis at the plant-level. The dynamic MFA tools developed in his thesis increase the granularity of models used for the simulation of metal cycles. These tools were applied to different case studies, including the monitoring of emissions in an aluminium smelter and scenarios for the future demand of materials for lithium-ion batteries and aluminium in cars.

Dr. Romain Billy (to the left) together with Prof. Daniel Müller during the PhD defense in 2022.

SAM - Society & Materials International conferences
SAM conferences are an international forum for exchanging ideas on new methodologies, new concepts and new issues that connect materials and society from different perspectives, ranging from social to engineering sciences.

The 11th meeting of the Society and Materials conference, SAM-11, took place in Trondheim, Norway on May 15 -16, 2017. 5 keynote lectures, 25 presentations and 10 posters were presented to an audience of 77 participants from 3 continents and 15 countries. In the introductory session, the pioneering and seminal role of NTNU in the fields of metals, society and societal metrics (MFA in particular) was emphasized. The chair of the scientific committee stressed the point that the conference was to bring together material "hard" sciences and social "soft" sciences. Moreover, the conference serves as an experimental laboratory, where new ideas are tested and discussed in terms of methodology but also of implementing them to solve strategic societal challenges: *"If it is not new or disrupting, don't bring it to a SAM conference!! If it does not connect both material and social dimensions, do not propose it either!"*

Highlights of scientific results
Metal production inevitably generates by-products and waste materials, their nature depending on the metal and its ore. The ore material always consists of other elements as well as the metal. Ore dressing or enrichment/refining processes are needed to make the ore more suitable for the subsequent metal extraction. Such processes are often carried out near the mine.



Participants to the 11th SAM conference, May 2017

Handling of by-products and waste have changed dramatically over the years. Waste materials that were previously landfilled without considering the impact on the environment are now increasingly considered resources. The assumption that the load on nature was negligible has changed radically. In addition, green movements have increasingly raised questions about what to do with waste materials and our common resources. Some of the waste materials can have significant value if used in other types of production. Systematic research will increase the understanding of the potential of such processes, as well as knowledge of new conversion opportunities of such residues. Through such research, it is in many cases possible to redefine waste materials as resources.

In RD 5, several master students and a PhD candidate associated with the SFI Metal Production have done work on the Pedersen process which is a method for producing alumina which is more resource efficient than the Bayer process. In the Pedersen process, the iron is removed from the red mud before the alumina is extracted from the ore. Thereby preventing the problem of bauxite residue (red mud) generation. The students managed to reproduce the process in lab-scale. This led to the start of a large European Horizon 2020 project called ENSUREAL in which the process was scaled up to pilot scale and several innovative aspects, like the iron reduction with hydrogen, were introduced. The process can also be used to process bauxite residue and the techno-economic analysis has showed that this is a profitable way to process the waste from the Bayer process.

Awards
Halvard Tveit (Elkem) and Leiv Kolbeinsen (NTNU) were honored with the prestigious Jean-Sébastien Thomas Prize in May 2019 at SAM 13 in Pisa, Italy. Their paper, titled "The (love and hate) role of entropy in process metallurgy," was recognized for its outstanding innovation in methodology, experience, and results.

Pyrometallurgical processing of bauxite in the Pedersen process.

Halvard Tveit and Leiv Kolbeinsen receiving the Jean-Sébastien Thomas Prize 2019.

RESULTS - KEY FIGURES

SFI METAL PRODUCTION 2015-2023

155 Scientific publications (peer reviewed)

176 Dissemination measures for users

71 Dissemination measures for the general public

45 Number of new/improved methods/models/prototypes finalised

1 New business activity

14

PHD DEGREES COMPLETED

80

MASTER DEGREES

FINANCING THROUGH THE LIFE OF THE CENTRE

SUMMARY SHEET FOR THE MAIN CATEGORIES OF PARTNERS (NOK MILLION)

Contributor	Cash	In-kind	Total
Host		41	41
Research partners		28	28
Companies	54	56	110
Public partners			0
RCN	96	-	96
Sum	**150**	**125**	**275**

DISTRIBUTION OF RESOURCES (NOK MILLION)

Type of activity	NOK million
Research projects	232
Common Centre activities	11
Administration	32
Total	**275**

INTERNATIONAL COLLABORATION

SFI Metal Production has formed a solid basis for development and expansion of our international activities, cooperation through international exchange of personnel, establishment of new network, education, and participation in conferences and projects. An important contribution to the internationalization is also our international scientific committee with well renowned scientist.

EU-PROJECTS

Partners in the SFI Centre have successfully brought forward eleven EU's framework projects as coordinators or partners within the research area of the Centre. Of these, eight projects are still running:

FET-Open – EU- Amadeus Next GenerAtion MateriAls and Solid State Devices for Ultra High Temperature Energy Storage and Conversion Amadeus (H2020, FET Open): Coordinator University of Madrid, Norwegian partner(s): NTNU/Merete Tangstad.

SecREEts – Secure European Critical Rare Earth Elements (H2020, IA): Coordinator SINTEF/Arne Petter Ratvik. Other Norwegian SFI partner(s): None.

RemovAl – Removing the waste streams from the primary Al-production and other metal sectors in Europe (H2020, IA), Coordinator: Aluminium of Greece, Other Norwegian SFI partner(s): NTNU, SINTEF, Elkem.

PREMA – Energy efficient, primary production of manganese ferroalloys through the application of novel energy systems in the drying and pre-heating of furnace feed materials (SPIRE, IA): Coordinator SINTEF/Eli Ringdalen. Other Norwegian SFI partner(s): NTNU, Eramet.

HARARE – "*Hydrogen As the Reducing Agent in the REcovery of metallurgical waste*". SINTEF and NTNU are partners. The project will demonstrate sustainable pathways to produce metals using hydrogen as an enabler. Hydrogen as a reductant to substitute carbon is one of the few ways metallurgical industry can potentially become truly free of CO_2-emissions. SINTEF is coordinating the project which has 10 partners from Greece, Germany, Belgium and Norway. The contact person is Casper van der Eijk.

SisAl Pilot – Innovative pilot for Silicon production with low environmental impact using secondary Aluminium and silicon raw materials. Coordinator NTNU/Gabriella Tranell. Other Norwegian SFI partners: Hydro, Elkem, Wacker.

SisAl Slag Valorization – The project SisAl Slag Valorisation coordinated by prof. Gabriella Tranell receives funding from the EU body EIT Raw Materials. The project is an acceleration action within the thematic area: Increased resources efficiency in mineral and metallurgical process. The duration of the project is from 2021-2023 and the total budget is about 4.8 M Euro.

ENSUREAL – Integrated cross-sectorial approach for environmentally sustainable and resource-efficient alumina production (SPIRE, IA): Coordinator SINTEF. Other Norwegian SFI partner(s): NTNU.

INTPART PROJECTS

(International Partnerships for Excellent Education, Research and Innovation)

INTPART projects focus on development of the two disciplines Education and Research. Several INTPART projects have been associated with the Centre during the Centre period.

INTPART-Metal Production (2018-2021).
The overall goal of the project was to establish and develop a long-term cooperation between the institutions of NTNU, SINTEF, MINTEK (South Africa) and North-West University (NWU, South Africa) regarding research and higher education. The main part of the project has been focusing on exchange of scientists and students for longer or shorter periods (18 research exchanges). In addition to contributing in 9 common courses and seminars the participants has also 7 published papers, 6 conference papers in common conferences and 7 common MSc thesis. A common chapter regarding use of carbon materials in ferroalloy and Si production was also done in the book New trends in coal conversion (Woodhead publishing series in energy). This project played an important role in establishing the EU-PREMA project as well.

Thanos - Thermodynamic from nanoscale to operational scale (2020-2023).
Professor Merete Tangstad received 5,6 mill NOK for the INTPART project “Thanos”. The cooperating partners in the project are NTNU and SINTEF in Norway, Mintek and North West University in South Africa, University of Science and Technology Beijing in China and the University of Tokyo in Japan. In this project the common theme is the use of thermodynamics in metal producing processes. During the project period there have been common seminars and workshops, exchange on a senior scientist and student level as well as common publications. Based in this project new collaboration in the area of primary metal production has been established.

INTPART-CaNAl - Norwegian-Canadian Partnership in Research and Education on Primary Production of Aluminium (2018-2021).
The project aims to build a long-term sustainable partnership between the Norwegian Al research community at NTNU/SINTEF with the Canadian counterpart at Laval University/REGAL. The 2nd Summer School on Research in Aluminum Production took place from October 7 to 10 at Laval University. The Laval members of the Norwegian-Canadian Partnership were proud to receive a delegation of 13 students and researchers from NTNU. The last day was reserved for a visit to the Alcoa smelter, located in Deschambault. The 1st Summer School was arranged in Trondheim in August 2018. The project also supported short visits and exchange of researchers and students between the two countries, involving five individuals in 2019.

EXTREME- Norwegian-American-German network in research and education of new alloys and coatings for space and other extreme environments (2020-2023)
Professor Gabriella Tranell received 5,7 mill for the INTPART project “Extreme”. The project is a collaboration between leading institutions from Norway (NTNU/SINTEF), the United States (Univ. of Connecticut, Univ. of Pittsburgh and Univ. of Virginia) and Germany (RWTH Aachen).

Development and production of new alloys and coatings that can withstand harsh conditions found in aerospace, metallurgical and biomedical applications are the focus of this project. Materials and coatings that need to withstand extreme corrosive, thermal and abrasive environments are in rapidly growing demand. Since material degeneration processes are often very similar, research into their production, properties and use is naturally inter-linked. Today, specialized groups located in different countries work on similar problems, while step-change progress requires new modes of collaboration across disciplines, countries and applications.

OTHER INTERNATIONAL COOPERATION

We have encouraged our researchers and students to participate in international collaboration and networking through funding applications, exchange, conference participation, courses etc. Under is a short description of some of our international activities.

Development and application of key big data technologies for mineral processing
New project from 2020 in collaboration with China. Funding from the RCN-call Chinese-Norwegian Collaborative Projects on Digitalisation. Project leader is Xiang Ma from SINTEF Industry.

Joint PhD collaboration - The Centre has collaborated with Oxford University. Joint PhD candidate Attila Covacs successfully defended his thesis in 2021. An institutional research collaboration with RWTH Aachen University has also been established with associated PhD and MSc exchange.

EIT (European Institute of Technology)
Raw Materials is an important instrument for international cooperation on a European level. The Centre host, NTNU is member of EIT with Maria Wallin as coordinator, and provides an arena for both primary and secondary raw materials for the Centre.

International Scientific committee (SC):
The Centre has an international scientific committee with four members of high standing.

International exchange of researchers - Visiting senior researchers from other countries and visits by personnel from the Centre to other competence Centres, have been very important for exchange of ideas and for input on the international development in science.

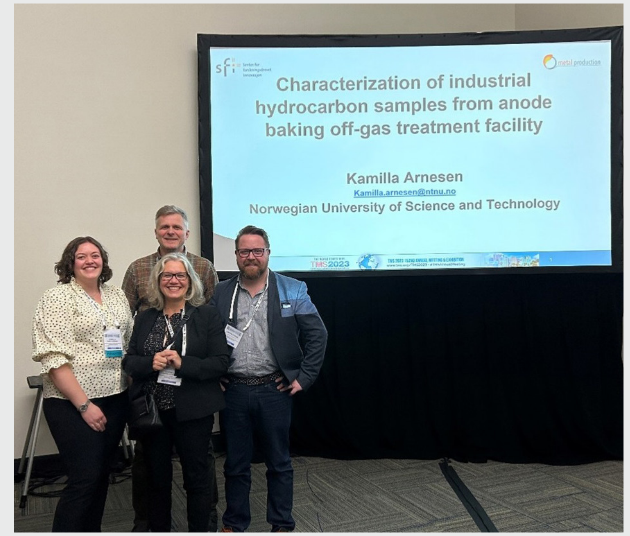
Book publication in 2021: "Principles of metal refining and recycling"
The book provides a self-contained introduction to the field of purification and recycling of metals. The texts cover thermodynamics, physical and transport properties, mixing, mass transfer and numerical models. It describes methods for removal of dissolved impurity elements, particles, and inclusions. It considers important aspects of the solidification process, remelting and adding of alloys. Recycling, future challenges and specific processes for each metal are discussed in detail.

Authors are Thorvald Abel Engh (NTNU), Geoffrey Sigworth (GKS engineering) and Anne Kvithyld (SINTEF). The work has been a collaboration with institutions in USA, Canada and Sweden and is partly funded by SFI Metal Production.

Author Anne Kvithyld, SINTEF, with the book "Principles of metal refining and recycling".

International courses and conferences are also an arena for connecting with international scientists. Several international courses and conferences with strong contribution from international scientists have been arranged, e.g. Silicon for the Solar and Chemical Industries Conference (2016, 2018, 2020), International CFD conference (2016, 2020), Aluminium refining and recycling short course (2016, 2018, 2019), SAM 11 Society and Materials – International Conference (2017), International Conference on Mathematical modelling (2016, 2018) and several short courses within production and refining of metals.

The Research partners and the user partners of the SFI are participating in conferences like TMS and the International Ferroalloys Congress (INFACON) not only with presentations, but also as appointed reviewers of papers and key-note speakers. The Centre hosted INFACON in 2021, with 310 participants from 29 countries.



PhD candidate Kamilla Arnesen gave a presentation at the TMS conference in 2023.

Participants from NTNU/SINTEF at the TMS conference 2022 (with facemasks due to the Covid pandemic)

TRAINING OF RESEARCHERS

RECRUITMENT AND DISSERTATIONS

Education of master and PhD students as well as postdocs is an important ingredient of an SFI Centre. Since the beginning of the Centre period SFI Metal Production has recruited 16 PhD candidates, 5 Postdocs and supervised approx. 45 master students. In addition, approx. 15 PhD candidates have worked on associated projects yearly. These are the PhD candidates and Post doctors that have joined the Centre since the beginning in 2015:

PhD candidate
Pyunghwa Kim

Research topic: Reduction mechanism in the SiMn process.

Defended his thesis in September 2018.

Supervisor: Prof. Merete Tangstad

PhD candidate
Massoud Hassanabadi

Research Topic: Electromagnetically Enhanced Priming of Surface Modified Porous Media.

Defended his thesis in December 2022

Supervisor: Prof. Ragnhild E. Aune

PhD candidate
Sethulakshmy Jayakumari

Research Topic: Silicon Carbide production during Silicon process.

Defended her thesis in August 2020.

Supervisor: Prof. Merete Tangstad

PhD candidate
Nicholas Smith

Research Topic: Oxidation of liquid Aluminium.

Defended his thesis in January 2019.

Supervisor: Prof. Gabriella Tranell

PhD candidate
Romain Billy

Research Topic: Material Flow Analyses of Aluminium.

Defended his thesis in December 2022

Supervisor Prof. Daniel Mueller and Prof. Leiv Kolbeinsen.

PhD candidate
Attila Kovács at Oxford University

Research Topic: Mathematical modelling of the alumina feeding in the Hall-Heroult process.

Defended his thesis in March 2021.

Co-supervised by Svenn Anton Halvorsen (NORCE) and Professor Kristian Etienne Einarsrud.

PhD candidate
Erlend Lunnan Bjørnstad

Research Topic: Interactions in Si refining.

Defended his thesis in August 2021.

Supervisor: Prof. Gabriella Tranell

PhD candidate
Håkon Myklebust

Research Topic: Modelling of dust formation and clustering in Ferroalloy Industry.

Defended his thesis in January 2022.

Supervisor: Prof. Gabriella Tranell

PhD candidate
Daniel Clos

Research Topic: Scaling in Al off-gas channels/heat exchangers.

Defended his thesis in May 2021.

Supervisor: Prof. Ragnhild E. Aune

PhD candidate
Benedicte Bårdsdatter Samsig

Research Topic: Biocarbon for manganese production.

Supervisor: Prof. Merete Tangstad

PhD candidate
Cathrine Kyung Won Solem

Research Topic: Parametric Study of Molten Aluminium Oxidation in Relation to Dross Formation.

Defended her thesis in November 2022

Supervisor: Prof. Ragnhild E. Aune

PhD candidate
Sindre Engzelius Gylver

Research Topic: Alumina Dissolution in Cryolite.

Defended his thesis in January 2023

Supervisors: Professor Kristian Etienne Einarsrud and Ass. Prof. Espen Sandnes

PhD candidate
Kamilla Arnesen

Research Topic: Polycyclic aromatic hydrocarbon emission from the metallurgical industry.

Defended her thesis in September 2023

Supervisor: Prof. Gabriella Tranell

PhD candidate
Hossein Salehi

Research Topic: Smelting phenomena of ilmenite and characteristics of the produced high titania slag.

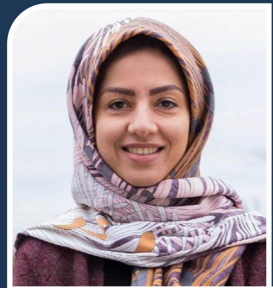
Supervisor: Ass. Prof. Jafar Safarian

PhD candidate
Haley Hoover

Research topic: Resitivity of Partially Transformed Materials in the FeSi/Si Process.

Defended her thesis in September 2023

Supervisor: Professor Merete Tangstad



PhD candidate
Hamideh Kaffash

Research topic: Dissolution kinetics of carbon materials in FeMn

Defended her thesis in August 2019

Supervisor: Professor Merete Tangstad

Postdoctor
Kai Erik Ekstrøm

Research Topic: Recycling of industrial by-products. 50:50 shared between SFI Metal Production and the Waste-to-Value project.

Supervisor: Prof. Gabriella Tranell

Postdoctor
Vincent Yves Canaguier

Research Topic: SiMn Production; process, reactions, kinetics and effects of the ore used.

Supervisor: Prof. Merete Tangstad

Postdoctor
Artur Kudyba

Research topic: Treatment and utilization of Al dross for other materials production.

Supervisor: Ass. Prof. Jafar Safarian

Postdoctor
Shokouh Haghdani

Research topic: Influence of structure on slag viscosity.

Supervisor: Professor Kristian Etienne Einarsrud

RECRUITMENT

To recruit talented students, we have tried to motivate and attract them to the Centre at an early stage of their studies. Summer jobs and projects have been offered to students at NTNU. The 5th year students have been introduced to relevant subjects in their specialization projects and MSc projects. The students have been working in close collaboration with PhD candidates, and we think this has motivated many of them to apply for PhD positions within the Centre and associated projects. All PhD students in the Centre have belonged to a "reference group". The purpose of these groups is to discuss the results and the plans for each individual PhD candidate. A reference group consists of the supervisor, representatives from other research partners, and most importantly, representatives from the industry partners. This ensures that the research done is relevant and in accordance with the needs in the industry and we believe that this has been great advantage for the progress and motivation for the PhD candidate.

There is a gender balance in the Centre both at the Professor level (3 of 6 are female) as well as in the student group (30-50% female), and hence no specific effort has been done to recruit women.

COURSES

The professors teaching courses in the 5-year MSc program use examples from the metal producing processes to familiarize the students with the industrial needs. Examples of courses are Material Production, Thermodynamics, Heat and Mass flow, Heterogeneous Equilibria and Phase Diagrams. There are courses in the higher classes more directly focused towards the subject important for the Centre like Refining and Recycling, Resources, Energy & Environment, and Metal Production. These courses have been important in order recruit 5th year students to research activities.

– WHERE DID THEY GO?

Students, PhDs and postdocs are exposed to timely scientific questions on topics highly relevant to the industrial partners. Through the close collaboration between research and industry partners these candidates learn the interplay between solving industrial questions and applied research. We believe that our candidates contribute to the shaping of a strong and sustainable green metal producing industry in Norway. PhD candidates who have worked at SFI Metal Production have continued their career in both academia and industry:

Centre industry partner	Other companies	University	Research institute	Outside Norway	Other	Total
3	6	2	2	1	2	16

We have asked a selection of our candidates to reflect on their experiences from being a PhD candidate in our Centre. Sethulakshmy defended her PhD thesis in 2020, Erlend in 2021 and Sindre in 2023. What are they doing today? And why are the results of their projects important to the industry?

Dr Erlend Lunnan Bjørnstad

Dr Sethulakshmy Jayakumari

PhD Candidate Sindre Engzelius Gylver

DR SETHULAKSHMY JAYAKUMARI

"The collaborations with scientific experts throughout my PhD helped me to make a good scientific relationship with academic and industrial experts in the field of metallurgy."

Date of Dissertation: 10.09.2020
Current position: Research Scientist, SINTEF
Title of thesis: *Formation and characterization of β- and α-Silicon Carbide produced during the Silicon/ Ferrosilicon process*
Supervisor: Professor Merete Tangstad

Can you give a short description of your PhD project and the major results?
Silicon carbide is one of the main intermediate compounds generated during primary silicon (Si) production in submerged arc furnaces. In my PhD work I investigated the formation processes as well as properties of SiC formed during the industrial production of Si. I predominantly analysed formation of different types of SiC from various carbon sources (charcoal, coal, and petroleum-coke) that are generally used in the industrial production of Si.

Analysing the characteristics of SiC produced from different carbon materials and the changes they undergo at higher temperatures are relevant to the Si industry and several other fields, including development of high-temperature power electronic devices.

My study identified and analysed the structures of SiC and the various polytypes formed in them, produced over a wide range of temperature (1647–2450 °C) attainable in laboratory-scale experiments.

The formation of Si in SiC particles was found to be directly proportional to increasing temperatures. The findings from my study prove that it is possible to produce Si in SiC particles quite higher up in the furnace, even at temperatures lower than 1800 °C, provided the partial pressure of SiO(g) is favourable.

Why is your project important to the industry?
Analysing the characteristics of SiC produced from different carbon materials and the changes they undergo at higher temperatures are relevant to the Si industry and several other fields. My studies provide the silicon industry with an insight into the key factors influencing Si production and intermediate formation of SiC in the process, and the importance of choosing the right carbon material, for efficiently producing Si.

Describe your experience from being a PhD candidate at the SFI
My PhD experiences at the SFI augmented me to grow as a scientist and as a person. The collaborations with scientific experts throughout my PhD helped me to make a good scientific relationship with academic and industrial experts in the field of metallurgy. The scientific projects, the publications from my work, the conferences that I attended, and the collaborations really helped me to pursue a scientific career in a reputed research-based organization as SINTEF.

Where did you start to work after the dissertation?
After my PhD I continued as a researcher for few months at NTNU department of materials science and engineering and after that I started as a research scientist at SINTEF Norway.

DR ERLEND LUNNAN BJØRNSTAD

"Good collaboration with silicon production industry ensured that my work was relevant to the industry."

Date of Dissertation: 18.08.21
Current position: Researcher, The process development department of Elkem Technology
Title of thesis: *Oxidative Ladle Refining of Metallurgical Grade Silicon: Refining of Ca and Al Impurities*
Supervisors: Professor Gabriella Tranell (main supervisor), Professor Hugo Atle Jakobsen and Dr. Jan Erik Olsen (co-supervisors).

Can you give a short description of your PhD project and the major results?
The goal of my project was to investigate the mass transfer of Ca and Al in oxidative ladle refining of metallurgical grade silicon, with the goal of improving industrial process control by expanding our knowledge of how the SiO_2-CaO-Al_2O_3 slag forms in the refining process. I created a theoretical framework utilizing previous findings from different fields and mathematical modeling, describing the key refining effects.

A major triumph of this project was the theoretical framework was used creating a lab-scale experimental setup which produced similar refining behaviors as seen in an industrial measurement campaign, indicating similarity between the theoretical framework and the actual industrial refining effects.

Why is your project important to the industry?
My project relates directly to the control of industrial refining of metallurgical grade silicon. Metallurgical grade silicon is used in a wide range of products, from solar-cells and electronics to the production of silicones and automotive aluminum and is listed as critical raw material by the EU. Improving process control helps with reaching the desired composition while reducing the amount of slag produced.

Describe your experience from being a PhD candidate at the SFI
My industrial reference group had representatives from silicon production industry (Elkem ASA and Wacker Chemie AG). The group assisted in my experimental and theoretical work and ensured that my work was relevant to the industry. The Centre gave me access to people from academia, research foundations, and the industry all at once, which was a great benefit for me.

Where did you start to work after the dissertation?
Currently, I work as a research engineer in the process development department at Elkem Technology. I mainly work with expanding Elkem's degree of digitalization and process control for process steps handling liquid alloy, while also supporting everyday production at Elkem's plants.

DR SINDRE ENGZELIUS GYLVER

"Being a part of the SFI has been extra motivational since our partners are interested and enthusiastic about our work."

Date of Dissertation: 20.01.2023
Current position: Project engineer at Hydro's research center, Årdal
Title of thesis: *Dissolution of alumina in cryolite*
Supervisors: Professor Kristian Etienne Einarsrud (main supervisor) and Associated Professor Espen Sandnes (co-supervisor).

Can you give a short description of your PhD project and the major results?
My PhD-projects aimed to obtain a better understanding on the formation and disintegration of so-called-rafts, which can occur when alumina is fed into a cell. So far, we have recorded and characterized rafts from an industrial cell, studied feeding at room temperature using a water model and developed a method to create and sample rafts under controlled conditions in a lab furnace. We have observed rafts to form in industrial cells and that a significant volume is due to pores and cavities inside the raft. These pores will enhance the buoyancy of the raft, but the origin of pores is not completely understood yet and work to identify sources is ongoing. Modelling using Computational Fluid Dynamics is also a major part of the project.

Further work aims to perform a parametric study of raft formation in an industrial cell, to identify how different types of alumina and fines affects the size and structure of rafts.

Why is your project important to the industry?
Alumina control is defined as a critical process within Hydro, and knowledge within this field is important. Smelters need to adapt their operations as the alumina received will have varying properties from shipment to shipment. Obtaining higher understanding of the dissolution will aid the smelters to run their cells at a higher energy efficiency and with reduced emissions, in particular perfluorocarbon gases (PFC).

Describe your experience from being a PhD candidate at the SFI
Being a part of the SFI has been extra motivational since our partners are interested and enthusiastic about our work. They have provided valuable feedback throughout my PhD and helped me to see how my work can be applied in practice. It has also been a benefit to be multiple PhDs that can support each other, and involvement of master and Bachelor students have been a great support to my work.

Where did you start to work after the dissertation?
I have started as a project engineer at Hydro's research center (Technology and Operational Support) in Årdal, where I work on keeping Hydro's smelters at a high and sustainable performance. Currently, I am working with providing operational support towards the plant located in Høyanger, and a project to estimate alumina distribution in cells through individual anodic current measurements. I believe that my PhD has gained me a fundamental understanding of the process, thus making me better prepared for my new position and giving me more opportunities.

COMMUNICATION AND DISSEMINATION ACTIVITIES

Research communication includes both communicating to research fellows through scientific publications, conference presentations etc, as well as communicating to user groups, the general public and policymakers. Scientists have a responsibility to build bridges between science, industry and society, and to transfer the new knowledge to potential user groups. SFI Metal Production has been visible at several internal and external/public arenas throughout the Centre period. Here are some examples.

NEWSPAPERS, VIDEOS, BLOGS AND POPULAR SCIENCE EVENTS


22 ØKONOMI

FORSKNINGSMILJØ PÅ FISKAA. Vil utvikle silisiumproduksjon helt uten utslipp av CO2 og NOX

Fiskaa-forskere sentrale i lover

Elkems forskningsmiljø på Fiskaa er tungt engasjert i et stort EU-prosjekt. Lykkes det, kan det gi silisiumproduksjon helt uten utslipp av CO2 og NOX.

The EU-project SisAL is led by Professor Gabriella Tranell and conducted in close collaboration with SFI partner Elkem. Fædrelandsvennen published an article about the project in 2022, describing the experiments at Elkem Kristiansand and the expected outcome for circular economy.


Forskningspolitikk

INNOVASJON

Sentre for forskningsdrevet innovasjon: Kunsten å koble forskning med verdiskapning

Hva har forskningssenteret Metal Production, som jobber med å redusere CO2-utslipp i metallindustrien, til felles med Foods of Norway, som lager dyrefôr av norske grantrær? Begge er sentre for forskningsdrevet innovasjon (SFI) som forsøker å finne løsninger på samfunnsutfordringer.

SFI Metal Production manager Aud Wærnes was interviewed in the journal Forskningspolitikk in 2021. The purpose of the article was to discuss how SFI Centres can contribute to major important shifts in industry and society.


E24! AKSJELIVE BØRS E24+ TIPS OSS Søk

DET GRØNNE SKIFTET

Kronikk: Coronakrisen kan føre til grønn omstilling

Har vi noe å lære av metallindustrien?

Aud Wærnes (Sintef), Benjamin Ravary (Eramet Norway), Gabriella Tranell (NTNU), Kari Håland (NTNU)

Henholdsvis leder i, leder for generalforsamlingen i, nestleder i og koordinator i senter for forskningsdrevet inovasjon (SFI) Metal Production

Publisert: 26. juni 2020

In 2020 E24 published a chronicle from SFI Metal Production: *How can the corona virus crisis boost the green shift?* The chronicle was a joint work between the Centre management and the industry partners.

The Industry Conference (Industrikonferansen) was organized in Bodø in 2021 and 2022. In connection with the conferences Dagens Næringsliv published separate magazines, including articles about SFI Metal Production and our projects.

From the 2021 Magazine:


Tapping av silisiumovn i pilotlaboratoriet ved NTNU/SINTEF i Trondheim. *Foto: Vegar Andersen / NTNU.*

– Bruk kraften i Norge!

Med store mengder grønn energi og lang tradisjon for metallurgisk industri, vil det være feil å eksportere kraften til utlandet. – Verdiskaping i Norge bør være hovedmålet, sier professor i prosessmetallurgi ved NTNU, Gabriella Tranell og Senior forretningsutvikler Aud Nina Wærnes i SINTEF Industri.

Derfor er det også viktig at Norge beholder plassen i ledelsen når det gjelder kompetanse på dette området som det også forskes intensivt på.

– SINTEF og NTNU leder en rekke større prosjekter for å komme frem til mer energieffektive lavutslippsprosesser, forteller Tranell.

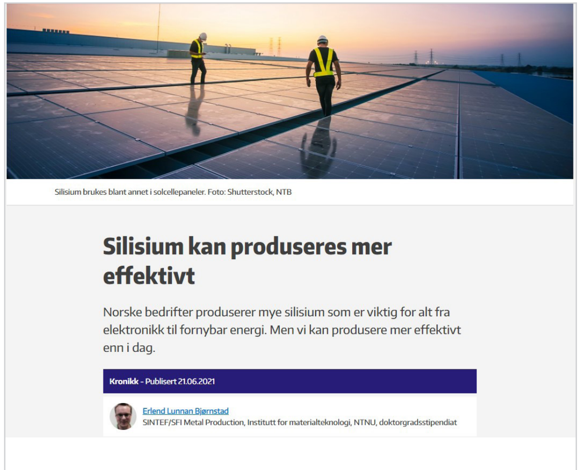
drogen i reduksjonsprosesser og utvikler en mer energieffektiv manganprosess (PREMA).

– I PREMA er målet å få frem en mer energieffektiv produksjon av manganlegeringer ved bruk av industrielle avgasser og solenergi – noe som vil

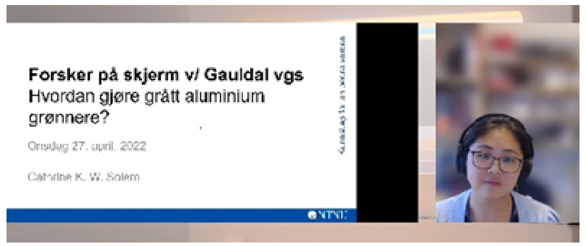
From the 2022 Magazine:


Forsker for bærekraftig metallproduksjon

Innenfor metallurgisk industri er det stadig sterkere fokus på løsninger for å gjøre næringen mer bærekraftig. Sintef og NTNU leder an i utviklingen.



Our PhD candidates and post doctors have actively contributed to dissemination of results to a broader audience. Their research has been presented in blogs, Forskning.no, Gemini and more.



Former PhD candidate Cathrine Kyung Won Solem has presented her work on a greener aluminium industry for high school students at **«Researcher on screen»**, organized by Trøndelag Fylkeskommune.

Former PhD candidate Sindre Gylver participated at **PhD Grand prix** in Trondheim in 2021. In this contest, PhD Candidates compete on explaining their research in an understandable and entertaining way.

FILMS

Several films about research on Metal Production have been produced during the Centre periode. They are available at our website: https://www.ntnu.edu/metpro/

OTHER INTERNAL AND EXTERNAL COMMUNICATION ACTIVITIES:

Time	Topic
Fridays 10:00 -10:45	14 Si Silicon
Fridays 11:00-11:45	25 Mn Manganese
Thursdays 15:00-15:45	13 Al Aluminium

Webinar series
From 2020 we have invited all SFI partners to attend digital webinars with 45 minutes scientific presentations every other week. The presentations are on the topics Silicon, Manganese and Aluminium. The webinars have been a success, and the responses from our industry partners have been highly positive. The webinars are easily available for everyone to join on Teams, with possibilities for interaction/ discussions.

SFI Spring and Autumn Meeting
SFI Metal Production has brought together all partners for joint meetings twice a year, the SFI Spring and Autumn meetings. The purpose of these meetings has been to exchange information on major results from the various research domains, as well as presenting overall thoughts and strategies important to the Centre development. Stakeholders from industry, NGOs and governmental agencies have been invited to the meetings.

All participants to SFI Metal Production Autumn Meeting 2022.

In addition to the Spring and Autumn meetings, the Centre has facilitated interaction and knowledge exchange between the partners in the Centre. **One-to-one meetings** have been organized with individual partners. The Research Domains (RD) have their own **discussion and planning meetings** with the industry involved, in the different research areas in addition to workshops and status meetings. The PhD student **reference groups meetings** have also been crucial to discuss the results and the plans for each individual PhD candidate.

EFFECTS OF THE CENTRE FOR THE RESEARCH PARTNERS

Metal production is one of the core industrial sectors in Norway and consequently one of the most important research and education areas at NTNU, the main technical university in Norway. NTNU covers the value chain, from raw materials to manufactured products, which includes research and education activities at several departments and faculties. The vision of the NTNU strategy is “Knowledge for a better word” and for the Department of Materials Science and Engineering – “Material Science and Engineering for a better world”. The focus in the Centre on reduced energy consumption, reduced emissions and environmental impact, directly relates to two of the NTNU strategic research areas Energy and Sustainability.

SFI Metal production has been at the core of the activity at NTNU, SINTEF and NORCE on metal production. It is essential to realise the ambition to strengthen and show our national position as the main education and research community.

Collaboration has strengthened the research on metal production in Norway

The SFI Metal production as a Centre has played an essential role in expanding the collaboration between the research groups. The partners in the Centre have long tradition for cooperation and are recognised for world leading competence within the scientific areas of the Centre. Further development of this cooperation, which is an excellent example of the triangle-model (university-institute-industry cooperation), has been stimulated by several means undertaken by the Centre;

- The management model of SFI Metal Production: NTNU is the Centre host and SINTEF is the Centre leader.
- The establishment of the common physical location: the physical Centre location on campus (Alfred Getz vei, Gløshaugen) with research partners, students and industry partners present in shared office environment is one important mean for collaboration.
- A well-functioning Centre management with representatives from different institutions.
- An active and engaged Centre board and Centre general assembly.
- The Centre has focused on establishing arenas for presentation and exchange of scientific results, both formal Centre meetings and seminars and more informal workshops and on-site visits to all the partners. During the Covid 19 pandemic, Webinars became very popular, and has continued ever after.
- Reference groups with all partners represented is established for the specific sub-tasks and PhD projects.
- The clear and ambitious focus on spin-off projects.
- Researchers at SINTEF and NORCE are co-supervising PhD candidates in the Centre.
- Engagement of one “Institute PhD”.
- Strong scientific networks both nationally and internationally.

The research partners’ position in the area of metal production has been significantly strengthened through SFI Metal production, benefiting both industry and society. We believe that the Centre is an important node in Europe to continue putting emphasis on the need for sustainable metal production in Europe in a future of resource constraints and increased environmental awareness.

SFI Metal production is based on the long standing and strong collaboration between NTNU and SINTEF. SFI Metal production has been instrumental for continuing to develop the research triangle between NTNU, SINTEF and industry, with NTNU as the main educational institution and SINTEF as the research institute. The Centre is organized with respect to research themes including activities in both organizations with interlinked objectives. This was deliberately done to secure that all partners work together within the different areas of the Centre. Also, the Centre Director Aud N. Wærnes is from SINTEF, while NTNU is the host institution. This is an excellent example of how SINTEF and NTNU jointly take advantage of resources and competence and illustrate the unique relationship between the two institutions. The introduction of NORCE, previously Teknova in the joint research activities, primarily on dust and fume and on modelling of alumina dissolution, has strengthened the national cooperation and increased the visibility of joint research interests and complementary competence. This has opened the door to new, joint project initiatives.

Students and PhD candidates from SFI Metal Production visiting Elkem in 2017. Photo: Elkem.

While NTNU already was recognised as the world leading university in the areas of aluminium and ferroalloys research and education, the Centre has worked as a visible node for attracting more partnerships and joint research. The Centre has organized and hosted several national and international conferences. Professors are also regularly invited to hold lectures at international conferences (TMS, INFACON, Gordon Research Conference, CRU etc.)

The Centre has produced more than 155 journal articles and a substantial amount of technical reports and conference contributions during the eight years period of the Centre. Co-publications with the industry partners have been quite substantial.

Researcher during an experiment in Bergbygget, NTNU Gløshaugen. Photo: Casper Van der Eijk

EFFECTS OF THE CENTRE FOR INDUSTRY AND SOCIETY AT LARGE

The strategy for the industry partners in the SFI Metal Production on a general basis, is to make the core processes more material and energy efficient with a lowest possible CO_2 footprint. This includes new raw materials, process development to improve furnace operations/yield, metal purity, sustainability, energy efficiency and reduced emissions. In the last years, the focus on CO_2 emissions has intensified. Strategies have been developed for reducing the CO_2 footprint by 50% within 2030, and carbon neutrality within 2050. The strategies to reach those goals are in principle three folded 1) replace fossil carbon with biocarbon, 2) develop new processes that are carbon neutral and 3) CCS/U or a combination of these technologies. The use of biocarbon in Silicon and Ferrosilicon is a relatively mature technology compared to new processes. For the aluminium industry, inert electrodes and new electrolysis process based on chlorine are the main technologies to carbon neutrality.

The industry partners in the SFI Metal Production reports that their overall activity related to R&D has increased significantly along with the participation in the SFI. The Centre has included important basic topics to the research portfolio, which trigger discussions in the internal R&D and operational practice in the industry. Results from the Centre support ongoing internal developments in process understanding and thereby enhance the industries competitiveness.

Here are some examples of improved processes and results that have been important for the industry:

Emission measurements in industrial off-gases: New measurement methods for PAH, knowledge of the distribution of the different types of PAH in the off-gas and more knowledge on PAH formation, resulted in an application for a project to the Research Council of Norway (RCN), PAHssion, read more in the chapter Research results.

Improved furnace productivity: Since 2008, several excavations of arc furnaces have been carried out in the Norwegian ferroalloy industry across different companies. Evaluation of findings from excavations of furnaces have given a unique opportunity to compare observations and data in order to understand the furnaces better and reveal possible problem areas that need to be addressed to improve furnace operation and productivity.

New knowledge on production of aluminum: The dissolution rate of alumina in the cryolite bath in aluminum electrolysis is important for both the utilization of raw materials and greenhouse gas emissions. The Centre has developed knowledge and models for better control of the dissolution rate, which have contributed to a more efficient electrolysis process with a higher current yield.

Increased knowledge about the combination of CO_2 cover gas and the use of Be in dross formation in the Al foundry, has provided increased process control and has triggered new internal tests regarding the reduction of dross formation, read more in the chapter Research results.

Three licenses on pragmatic modelling have been finalised between a R&D partner and the industry – two on aluminium and one on ferromanganese.

Pragmatic model for bath flow dynamics in aluminum reduction cells: The software developed on Aluminium is designed to simulate the flow of liquid bath in an aluminum reduction cell, and critical phenomena for cell operation, in such a way that it can be used for process control and optimization of cell operation. Both Hydro and Alcoa have a License Agreement with SINTEF.

COMSOL model for (Fe)SiMn pilot furnace: NORCE has developed an overall model for the pilot-scale (ferro)silicomanganese furnace. The model takes into consideration the material flows, process chemistry, electrical and thermal conditions of the furnace. Key process parameters predicted by the model—such as slag and alloy production rates, slag-to-alloy and silicon-to-manganese ratios, and the furnace efficiency—are in agreement with values measured in experiments. The model is implemented in COMSOL Multiphysics.

Norsk Hydro AS has been granted a patent with the title; "Method for and equipment for suppressing discoloration of Al-Mg products". The patent is partly based on the thesis of PhD Nicholas Smith-Hansen from 2018 where CO_2 was used as cover gas to prevent oxidation and discoloration at high temperatures.

Start-up company

The development and evaluation of using affordable measuring systems for dust has been an important achievement. Through a collaboration between NTNU and SINTEF, it was demonstrated through campaigns in the Al-, Si- and Mn industries that small portable sensor systems can be effectively used to monitor the dust-load in the in-door environment of metallurgical industries. PhD Håkon Myklebust has a Start-Up company based on the technology. The Scientific Committee has made a closing report for the SFI. The main statements can be summarized as follows:

- The experimental capability and link to reality, are so unique as there are very few groups that still do this well and link it to simulation and modelling, documented through numerous scientific publications, books etc. This is the standout achievement of the SFI Metal Production, , a place to go globally, where fundamental knowledge is generated as well as the fundamental aspects such as modelling, simulation and fluid flow simulation techniques (multi-physics).
- Compared to others, SFI Metal Production has all core-research teams in Trondheim (SINTEF and NTNU), and real close research collaboration has been made and resolved several key industrial problems. Trondheim is one of very few places where many world-leading experts in pyrometallurgy are present. So, this strength should be kept for the development of pyrometallurgical industries of Norway, Europe and the entire world.

Close cooperation and competence transfer

The Centre has encouraged mutual exchange of personnel between the industry and the R&D partners. Staffs from the SFI including summer students, have participated in test campaigns at industrial sites. Examples are excavations of furnaces in the ferroalloy industry, studies of scaling phenomena in the aluminium industry and PAH/emissions measuring campaigns. The SFI Centre has access to excellent laboratories with up-to-date equipment in small, medium and pilot scale. SFI Metal Production is the fundament for a new Research Infrastructure Support for Establishment/Upgrades of Research Infrastructure of National Importance. The title is "Transition to Sustainable Resource Efficiency in Metal Production and Recycling (TEMP)". The TEMP project was funded by the Research Council in 2022 and is now in the phase of purchasing equipment covering future process developments for the metallurgical industry.

The Centre has been a hob for development of new ideas and constitute a stronghold when it comes to competence and skills. This is actively utilised in establishing new projects as INTPART, KPN and IPN projects together with other universities, and/or the industry partners both inside and outside the Centre.

THE INDUSTRY PARTNERS SUMMARIZED THE VALUE OF SFI PARTICIPATION IN A STRATEGY MEETING IN 2020:

BUILDING COMPETENCE AND KNOWLEDGE

The size of the Centre and the longterm commitment facilitate in-depth interdisciplinary activities. Members from industry build competence and establish research groups within the core areas. Also the activities bring people together, from groups who normally would not easily meet or collaborate. The knowledge gained from the Centre participation is implemented in the day to day decisions.

NETWORKING

Participants in the SFI expand their network with people from academia, institutes and other industry members. The network is a significant resource for discussions and problem solving. Spring meeting, Autumn Meeting, seminars and webinars are important areas for networking.

BRANDING

Participation in an SFI gives a comparative advantage. The commitment to the SFI shows that we are innovative and willing to invest in knowledge building. Students that have visited industry partners (summer jobs, experiments etc) become good ambassadors for the industry.

RECRUITMENT

SFI participation motivates the employees. By choosing to be an SFI partner we recognize the need for new knowledge and give opportunity to be involved in innovation activities. When recruiting new people, we present the advantages of SFI participation.

SPIN OFFS/INNOVATIONS

Results from the SFI are implemented in the industry, or are starting points for new innovation projects. New ideas, new processes and new strategies have appeared as result of the SFI.

FUTURE PROSPECTS

The Centre has successfully built up a portfolio of associated and spin-off projects to sustain the research effort beyond the SFI Centre period. So far 11 EU projects have been granted, 10 IPN projects, 11 KPM/KSP projects and 4 INTPART projects with a total budget of 1,5 billion NOK. Several project applications both to the EU and the Research Council of Norway are pending. The portfolio has been built on the competence developed in the Centre and expanded year by year giving a broad range of projects covering all topics from the SFI Metal Production. As such, the SFI has served as a competence pool and a place for developing new ideas in close cooperation with the industry partners. Due to an excellent international network developed in the Centre, the EU portfolio has increased over the Centre period and is now the far biggest contributor to research for the R&D partners in the Centre.

The partners of the SFI Metal Production see a need for continuing the Centre as a basis for long term research and will apply for a FME with the title "Climate Neutral Metal Production" in November 2023. The partnership includes the SFI Metal Production partners and other metal production companies. Metal production is energy intensive and a significant contributor to greenhouse gas emissions. The need to reduce the environmental footprint has become increasingly pressing as the world works to address the challenges of climate change. We propose a portfolio of research tasks aiming at both the medium- and long-term goals for reduction of climate gas emissions.

The industry partners of the SFI Metal Production are funding an interim period while working for continuation of the most successful Centre activities. Some of the strategic, important activities in the SFI will be continued, like Webinars, summer students and an annual meeting with the aim to present results from associated projects. Some examples of topics that are followed up for commercialisation by the industry:

- BioCarbon in the ferroalloy industry - The competence developed on alternative reductants like charcoal, is now a basis for further research in The Norwegian Ferroalloy Producers Research Association (FFF)and strategies are made for how to address the new challenges with mitigation of CO_2 emissions where use of BioCarbon is the only option for the ferroalloy industry in the short term.

- Aluminium is produced in the Hall-Héroult reduction cell where aluminium oxide, dissolved in a cryolite bath is the raw material and is reduced at the cathode, creating aluminium. In 2020, there were no options for reusing surplus bath from the aluminium electrolysis. A pre-study was initiated in the Centre that formed the basis for a new IPN project "BADELand – Recovery of valuable surplus bath components from Aluminium Electrolysis" with Hydro, Alcoa, and Floursid Noralf, a supplier of aluminium fluoride to the aluminium industry. The project has successfully demonstrated a path for recovery of aluminium fluoride from the bath.

- Manganese alloy production is energy-intensive and accounts for large amounts of CO_2 emissions. New ideas were investigated in the Centre and experiments were carried out in our Pilot furnace. Relevant competence and infrastructure were the basis for an EU Horizon 2020 project in 2018. PREMA – "Energy efficient, primary production of manganese ferroalloys through the application of novel energy systems in the drying and pre-heating of furnace feed materials". The project has demonstrated technologies for manganese ore pre-treatment that utilise energy and material streams more efficiently and decrease CO_2 emissions.

- New models and methods, and a start-up company on dust sensors are based on activities in the Centre. For further details see the chapter "Effects of the Centre for industry and society at large".

NTNU and SINTEF are sharing a unique laboratory infrastructure within the area of SFI Metal Production. The infrastructure has been developed during decades and are used on a daily basis. Further strengthening of this infrastructure is facilitated by the funding from RCN through the TEMP project, as well as through in-kind contributions from SINTEF and NTNU.

The deliverables from the Centre in the form of reports, articles, memos etc are available for the industry partners. The Centre has made s system for easy access to the relevant data based on Sharepoint and eRoom.

CONCLUSION

REFLECTION ON SUCCESS FACTORS FOR THE SFI CENTRE MODEL

It has been important for SFI Metal Production to re-iterate the main objectives and set clear scientific/technical goals for what the Centre wants to achieve, beyond and around the SFI funding. It has also been important for the Centre to be involved as a team in national and international process industry initiatives and developments (e.g., Prosess21, EU SPIRE/Horizon 2020 etc.) and to lift the industry profile and vision for metal production in Norway. To achieve the goals the Centre Management and the Executive Committee decided at an early stage to develop a Strategy and Long-Term Plan for the Centre. The plans were followed up in annual strategy meetings. Important values and strategies for the Centre have been discussed and defined by the Executive- and Innovation Committee. Potential innovations from the Centre have been discussed and registered.

A process for developing the Annual Workplans was put in place to secure partner involvement and commitment. The work included meetings between the R&D and the industry partners with respect to scientific content and corresponding in-kind contribution. Drafts of the plan were available for the partners for comments before the General Assembly formally approved the plans.

The research work has been divided into five different Research Domains (RD). The competence goals and associated activities were defined at an individual RD level. The PhD students and the researchers worked with activities that were complementary or they worked on the same topic with different approach. The industry partners participated actively in research activities and meetings. The Research Domains leaders continuously searched for joint activities bridging the different RDs. The PhD students were part of individual resource groups with members from industry partners to ensure close contact and relevance of the research activity.

The Management Team has consisted of the five RD leaders, the Centre Manager, and the Centre Coordinator. Activities defined in the five RDs were discussed and coordinated by the team. The team has collaborated effectively through the Centre period, organised meetings and followed up deliverables in close collaboration with the Executive Committee, General Assembly and individual partners.

Communication and understanding between the partners and a wish to succeed together as a team, is the key for a successful Centre building. Meetings and events for both formal and informal discussions have been organised and the Centre has acted as a hub for R&D and industry collaboration. Also, PhD students from the Centre as well as associated PhD students have worked together on both a scientific and a social level. The establishment of a physical location of the Centre on the campus with research partners, students and industry partners present in shared office environment, has made a very positive contribution to the collaboration in the Centre.

Centre meetings have been organised bi-annually throughout the Centre period – Autumn and Spring meetings. Invited speakers from industry and other organisations have given inspiration and insight to the Centre partners. Scientific achievements were always a

priority in these meetings that were well visited by the industry partners. In addition, "One to One" meetings with the individual industry partners and Webinars have been organised in order to disseminate results from the Centre to operators and staff that normally are not participating in physical meetings at the Centre.

Research communication includes both communicating to research fellows through scientific publications, conference presentations etc. as well as communicating to user groups and the general public. SFI Metal Production has been visible through the web site, Annual Reports, news feeds, blogs and numerous public events. Several videos from our activities have been produced.

One important key to success for an SFI is to secure involvement of the industry partners in the scientific as well as the strategic and innovation activities.

ANNUAL ACCOUNTS 2015-2023

Accounting report 2015-2023- Project Characteristics and Costs (All figures in 1000 NOK)

Item	NTNU	SINTEF AS	SINTEF Energi	NORCE	Hydro	Eramet	Elkem	Alcoa Norway AS	Eramet Titanium & Iron	REEL	Wacker	Finnfjord	Ferroglobe Mangan Norway*	FESIL**	Total cost
RD1	8 100	12 475	0	5 953	4 044	1 133	866	734	19	20	126	0	97	30	33 597
RD2	29 247	25 634	0	225	498	9 178	4 305	780	1 931	18	1 202	837	1 175	104	75 134
RD3	25 695	19 209	0	0	4 811	25	953	1 789	11	0	30	33	13	36	52 605
RD4	22 153	12 869	5 794	2 003	4 485	4 569	1 481	1 712	62	1 987	95	142	0	44	57 395
RD5	6 945	4 211	0	0	974	211	383	138	36	28	35	57	45	14	13 077
Equipment															0
Adm.	22 107	16 137	0	0	985	612	698	602	627	139	315	576	86	28	42 914
Total budget	114 248	90 535	5 794	8 180	15 797	15 729	8 685	5 755	2 686	2 192	1 802	1 645	1 416	256	274 721

* *Industry partner 2015-2019*
** *Industry partner 2015-2016*

Accounting report 2015-2023 - Funding (All figures in 1000 NOK)

Item	NTNU	SINTEF AS	SINTEF Energi	NORCE	Hydro	Eramet	Elkem	Alcoa Norway AS	Eramet Titanium & Iron	REEL	Wacker	Finnfjord	Ferroglobe Mangan Norway*	FESIL**	RCN Grant	Total funding
RD1	3 015	3 561	0	1 593	8 134	1 806	1 780	1 594	139	111	168	20	150	80	11 520	33 672
RD2	10 674	11 756	0	46	964	13 036	8 815	1 619	4 790	105	2 012	1 464	2 081	237	17 367	74 964
RD3	8 815	6 126	0	0	9 526	78	1 812	4 249	58	20	63	68	44	52	21 692	52 603
RD4	8 175	937	1 152	420	9 351	6 490	3 494	4 000	192	3 491	402	364	20	88	18 851	57 425
RD5	2 433	778	0	90	2 236	699	919	494	225	95	132	134	128	48	4 676	13 087
Equipment																0
Adm.	8 009	1 105	40	25	1 926	3 209	1 506	1 470	1 282	370	704	975	392	65	21 891	42 969
Total budget	41 121	24 263	1 192	2 174	32 137	25 318	18 325	13 425	6 686	4 192	3 481	3 025	2 815	569	95 998	274 721

* *Industry partner 2015-2019*
** *Industry partner 2015-2016*

STAFF

LIST OF POST-DOCS, CANDIDATES FOR PHD AND MSC DEGREES DURING THE FULL PERIOD OF THE CENTRE

Postdoctoral researchers with financial support from the Centre budget

Name	M/F	Nationality	Scientific area	Years/period in the Centre	Main contact
Sebastien Letout	M	Frace	Modelling of SiMn furnace/Comsol	2015-2017	Merete Tangstad
Heiko Gaertner	M	Germany/Norway	PAH standardisation (50%)	2016-2018	Gabriella Tranell
Elmira Moosavi Khoonsari	F	Canada	Thermodynamic modelling, environment and energy	2017-2017	Gabriella Tranell
Kai Erik Ekstrøm	M	Norway	Waste to resource	2017-2018	Gabriella Tranell
Vincent Yves Canaguier	M	France	Manganese	2018-2020	Merete Tangstad
Shokouh Haghdani	F	Iran	Influence of structure on slag viscosity	2019-2021	Kristian Einarsrud
Artur Kudyba	M	Poland	Dross utilization	2019-2021	Jafar Safarian

PhD candidates who have completed with financial support from the Centre budget

Name	M/F	Nationality	Thesis title	Years/period in the Centre	Supervisor
Massoud Hassanabadi	M	Sweden	Characterisation of Alumina Based Ceramic Foam Filters (CFFs) – An Experimental and Modelling Approach	2015-2018	Ragnhild Aune
Pyunghwa (Peace) Kim	M	Korea	The Reduction Rates of SiMn Slags from Various Raw Materials	2015-2018	Merete Tangstad
Sethulaksmy Jayakumari	F	India	Formation and characterization of β-and α-Silicon Carbide produced during Silicon/Ferrosilicon process	2015-2020	Merete Tangstad
Nicholas Smith	M	USA	Methods of Oxidation Inhibition for Al-Mg Alloys	2015-2018	Gabriella Tranell
Erlend Lunnan Bjørnstad	M	Norway	Oxidative Ladle Refining of Metallurgical Grade Silicon: Refining of Ca and Al Impurities	2016-2021	Gabriella Tranell
Håkon Myklebust	M	Norway	Fume Formation and Measurements in the Metal-Production Industry	2016-2021	Gabriella Tranell
Daniel Clos	M	Spain	Formation of Hard Grey Scale (HGS) on the Surface of a Cold-finger in the Aluminium Production Industry	2016-2021	Ragnhild Aune
Hamideh Kaffash	F	Iran	Dissolution kinetics of carbon materials in FeMn	2016-2019	IMA, NTNU
Romain Guillaume Billy	M	France	Monitoring and simulating material cycles and emissions at multiple scales - Case studies for aluminium	2017-2021	Daniel B Müller
Attila Kovacs	M	UK	Modelling the feeding process for aluminium production	2017-2020	Oxford/S.A. Halvorsen/K.E. Einarsrud
Cathrine Kyung Won Solem	F	Norway	Parametric Study of Molten Aluminium Oxidation in Relation to Dross Formation at Laboratory and Industrial Scale	2018-2022	Ragnhild Aune
Sindre Engzelius Gylver	M	Norway	Feeding of Alumina in Molten Cryolite Bath	2018-2022	Kristian Einarsrud
Kamilla Arnesen	F	Norway	Hydrocarbon Emission from the Metallurgical Industry	2018-2023	Gabriella Tranell
Haley Hoover	F	USA	Electrical Properties of Si furnace charges and materials	2019-2023	Merete Tangstad

Post-doctoral researchers working on projects in the Centre with financial support from other sources

Name	M/F	Nationality	Scientific area	Years/period in the Centre	Source of funding
Caoimhe Rooney	F		Modelling	2016-2019	KPN project ElMet, Teknova
Mertol Gökelma	M	Turkey	Refining Al	2018-2019	IPN project, Hydro
Sergey Bublik	M	Russia	Tapping Mn	2018-2021	KPN project, Controlled Tapping
Dmitry Sukhomlinov	M	Russia	Pre-reduction Mn	2018-2020	PreMa- H2020
Hamideh Kaffash	F	Iran	C dissolultion in ferroalloys	2019-2021	BioCarbUp
Gerrit Surup	M	Germany	Biocarbon	2019-2021	Reduced CO_2
James Mwase	M		Alumina extraction from slag	2019-2021	Endureal
Katarina Jakovljevic	F	Serbia	PAH emissions	2020-2022	PAHssion

PhD candidates who have completed with other financial support, but associated with the Centre

Name	M/F	Nationality	Thesis title	Years in the Centre	Supervisor	Source of funding
Karin F.Jusnes	F	Norway	Phase transformations and thermal degradation in industrial quartz	2016-2020	Merete Tangstad	IPN project High Temp Quartz, Elkem
Raghed Saadieh	M		TBD - FeSi operation	2016-2023	Merete Tangstad	Industrial PhD, Elkem
Mads Fromreide	M	Norway	Electromagnetic models of three-phase AC furnaces. Applications in metallurgical processes	2016-2020	Svenn Anton Halvorsen	KPN project ElMet, Teknova
Fabian Imanasa Azof	M		Pyrometallurgical and Hydrometallurgical Treatment of Calcium Aluminate-containing Slags for Alumina Recovery	2017-2019	Jafar Safarian	IMA, NTNU
Jian Meng Jiao	M	China	Si-based phase change materials in thermal energy storage systems	2017-2019	Merete Tangstad	Amadeus, H2020
Luis Carlos I. Bracamonte	M		Development of an electrochemical sensor for alumina concentration measurements and dissolution characteristics of alumina in cryolite melt	2017-2020	Espen Sandnes	IMA, NTNU
Andrea Broggi	F		Condensation of SiO and CO in silicon and ferrosilicon production	2017-2021	Merete Tangstad	IPN project SiNOCO2, Elkem
Trine Asklund Larssen	F	Norway	Prereduction of Comilog- and Nchwaning ore	2017-2021	Merete Tangstad	FME HighEff
Marit Buhaug Folstad	F	Norway	Slag in the Si and FeSi furnace	2017-2023	Merete Tangstad	KPN project, Controlled Tapping
Are Bergin	M	Norway	Ceramic Foam Filters (CFFs) for Aluminium Melt Filtration - Stability, Compression, and Performance	2018-2022	Ragnhild E Aune	Industrial PhD, Hydro
Leif Sigurd Storlien	M	Norway		2018-2020	Merete Tangstad	Industrial PhD, Ferroglobe
Adamantia Lazou	F	Spain	Reduction of bauxite and Al-containing waste to produce calcium aluminate slags and iron	2018-2020	Jafar Safarian	ENSUREAL, H2020
Trygve S. Aarnes	M	Norway	The effect of hydrogen and methane containing gasses on SiC and SiO formation	2018-2022	Merete Tangstad	KPN project Reduced CO_2
Trygve L. Schanche	M	Norway	Pretreatment of manganese ores in $CO/CO_2/H2$ atmospheres	2019-2022	Merete Tangstad	KPN project Reduced CO_2
Tichaona Mukono	M	Zimbabwe	Ferromanganese Production from Pretreated Manganese Ores: From Laboratory scale to Pilot scale	2019-2022	Merete Tangstad	PreMa-H2020
Vegar Andersen	M	Norway	Flue gas recirculation in the Si process	2020-2022	Gabriella Tranell	FME HighEFF
Alicia Vallejo Olivares	F	Spain	The effect of compaction and thermal pretreatment in Al recycling	2019-2023	Gabriella Tranell	Alpakka project
Harald Philipson	M	Sweden	Aluminothermic production of silicon	2020-2023	Kristian Einarsrud	SisAl Pilot
Azam Rasouli	F	Iran	Magnesothermic production of MG-Si and Silane	2019-2023	Gabriella Tranell	FME susoltech
Ece Soylu	F	Turkey	REcovery of metals from MSWI flyash	2022-2025	Gabriella Tranell	IPN Askepott
Vishal Rimal	M	India	Flow of slag in Mn-ferroalloy furnaces	2022-2025	Merete Tangstad	Recursive

MSc candidates related to the Centre research agenda and supervisor from the Centre staff

Name	M/F	Nationality	Thesis title	Year(s) in the Centre	Supervisor
Rune H. Stana	M	Norway	Solidification of Titanium Slags and Influence on Post Processing	2015-2016	Leiv Kolbeinsen
Joakim Holtan	M	Norway	Metallproduserende reaksjoner i silikomangan produksjon: nedsmeltingsmekanisme.	2015-2016	Merete Tangstad
Håkon Olsen	M	Norway	Theoretical study and mathematical modelling on the reaction rates in the SiMn-production process	2015-2016	Merete Tangstad
Erlend L. Bjørnstad	M	Norway	Mass Transfer Coefficients and Bubble Sizes in Oxidative Ladle Refining of Silicon	2015-2016	Gabriella Tranell
Claudios Sanna	M	Italy	Boron Removal from Molten Silocon by Gas Blowing Using Different Gas Mixtures	2015-2016	Gabriella Tranell/ Jafar Safarian
Siri Marie Bø	F	Norway	Phases and Zones in the Silicon Process	2015-2016	Merete Tangstad
Sofie Aursjø	F	Norway	Wear of Carbon Refractory Materials in Silicon Furnaces	2015-2016	Merete Tangstad
Karin Fjeldstad Jusnes	F	Norway	Parameters Affecting Softening and Melting of Quartz	2015-2016	Merete Tangstad
Marthe Erdal Kjeldstali	F	Norway	Kinetics and Mechanism of Phase Transformations from Quartz to Cristobalite	2015-2016	Merete Tangstad
Askhay Bhat	M	India	Boron removal from silicon using gas refininf and different crucible materials	2015-2016	Gabriella Tranell/ Jafar Safarian
Thomas By	M	Norway	Briquetting of Manganese Oxide Fines with Organic Binders	2015-2016	Merete Tangstad

Paul Guillaume Datin	M	France	Metal loss comprehension	2015-2016	Eli Ringdalen (SINTEF)
Katrine Holm	F	Norway	The Properties of Calcined Anthracite	2015-2016	Merete Tangstad
Nina Kvitastein	F	Norway	Distribution of Phosphorus between FeSi/Si and CaO-SiO_2 Slags at 1600 degree celcius	2016-2017	Gabriella Tanell
Trine Asklund Larssen	F	Norway	Reduction of MnO and SiO_2 from Assmang and Comilog based Slags	2016-2017	Merete Tangstad
Stine Svoen	F	Norway	Reduction Mechanisms in Manganese Ore and Deposition of Carbon from Natural Gas	2016-2017	Merete Tangstad
Stine Pettersen Espelien	F	Norway	Purification of Silicon Through a Hydrometallurgical Process	2016-2017	Jafar Safarian
Hanne Sellæg	F	Norway	Iron sepration from bauxite through smelting-reduction process	2016-2017	Jafar Safarian
Karoline Aasen Nilsen	F	Norway	Study of a Graphite Sensor for Alumina Concentration Measurements in Cryolite Melts	2017-2018	Espen Sandnes
Cathrine Kyung Won Solem	F	Norway	Experimental Study of the Thermal Stability and Chemical Reactivity of AlPO4-Bonded Ceramic Foam Filters (CFFs) in Contact with Molten Aluminium	2017-2018	Ragnhild Aune
Sindre Engzelius Gylver	M	Norway	Alumina Dissolution in Cryolite Melts	2017-2018	Kristian Etienne Einarsrud
Trygve S. Aarnæs	M	Norway	Removal of Aluminium Carbide from Liquid Aluminium	2017-2018	Gabriella Tranell
Sarel Johannes Franco Gates	M	South Africa	Fume suppression in a FeMn system with a increase in water content in the atmosphere	2017-2018	Gabriella Tranell
Gina Opstad Andersen	F	Norway	Surface treatment of high performance multicrystalline silicon wafers	2017-2018	Gabriella Tranell
Bettina Grorud	F	Norway	Interaction of Eutectic Fe-Si-B Alloy with Graphite Crucibles	2017-2018	Merete Tangstad
Hanne Mette Hustad	F	Norway	Tapping of FeSi Furnaces	2017-2018	Merete Tangstad
Kevin Lim	M	Australia	Recovery and Utilisation of Kerf Waste from Silicon Wafering Process	2017-2018	Gabriella Tranell
Ingrid Meling	F	Norway	Recycling and Utilisation of Secondary Aluminium Products	2017-2018	Gabriella Tranell
Matthew Engel Wermers	M	USA	Recycling of Fine Silicon Particles for Solar Grade Silicon Production	2017-2018	Jafar Safarian
Fredrik Rudjord	M	Norway	Recycling of Glass Wool Waste	2017-2018	Merete Tangstad
Loius Monnier	M	France	Material flow analysis of Hydro's aluminium plant in Sunndal, MSc over 2 semester	2018-2019	Daniel Muller

Åste Hegglid Follo	F	Norway	Alumina dissolution in Hall-Héroult cells	2018-2019	Kristian Etienne Einarsrud
Eirik Andre Nordbø	M	Norway	Formation of α-SiC in the silicon production process	2018-2019	Merete Tangstad
Azam Rasouli	M	Iran	Slag-Si equilibrium in different container materials	2018-2019	Jafar Safarian
Sofie Verschraegen	F	Belgium	Recycling of aluminium containing multilayer packaging	2018-2019	Leiv Kolbeinsen/ Anne Kvithyld
Sigvart Hansen Eggen	M	Norway	Remelting of aluminium packaging	2018-2019	Leiv Kolbeinsen/ Anne Kvithyld
Maria Renkel	F	Norway	Pragmatic CFD-modeling of alumina feeding	2020-2021	Kristian Etienne Einarsrud
Tommy Pedersen	M	Norway	Elektrisk ledningsevne SiC	2019-2020	Merete Tangstad
Benjamin Dale Hosum	M	Norway	SiMn reduksjon	2019-2020	Merete Tangstad
Eskil Christiensen	M	Norway	Numerical Modeling of Hydrogen Fluoride Adsorption	2020-2021	Kristian Etienne Einarsrud
Vegard Aulie	M	Norway	Dispersion and dissolution of alumina in cryolite melts	2019-2021	Kristian Etienne Einarsrud
Henning Dahl	M	Norway	Fuming from FeSiMg alloys	2020-2021	Gabriella Tranell
Sigmund Forberg	M	Norway	SiMn Reduction - comparison of charcoal and coke	2020-2023	Merete Tangstad
Mads Urang Nilsen	M	Norway	Using AERMOD to predict the dispersion of emissions from the aluminum industry	2021-2022	Kristian Etienne Einarsrud
Simen Bekkevoll	M	Norway	Alumina Dissolution in Cryolite Melts: Effects of Secondary Alumina Properties on Dissolution and Raft Behavior	2021-2022	Kristian Etienne Einarsrud
Veronica Milani	F	Italy	Saltflux properties in Al recycling	2021-2022	Gabriella Tranell
Erlend Hauge	M	Norway	Scaling in Silicon Furnaces	2021-2022	Gabriella Tranell
Solveig Høgåsen	F	Norway	Compaction and Al recycling	2021-2022	Gabriella Tranell
Fride Müller	F	Norway	Heavy Metal Emissions from Al industries	2021-2022	Gabriella Tranell
Per Fredrik Daun	M	Norway	A Comparative Study of Different CFD-codes for Fluidized Beds	2022-2023	Kristian Etienne Einarsrud
Jonas Melhus	M	Norway	Atmospheric Dispersion Modelling of Diffuse Emissions in Metallurgical Industry	2022-2023	Kristian Etienne Einarsrud
Jonas Foshaug	M	Norway	Reduced Illmenite Pellet dissolution in slag	2022-2023	Gabriella Tranell
Mathilde Meling	F	Norway	REcycling and REfining of Kerf and SisAl metal	2022-2023	Gabriella Tranell
Fredrik Sørli	M	Norway	REfining of Si	2022-2023	Gabriella Tranell

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